N 62 10978

LAC/379280 NASA CONTRACT NO. NASr-59

INVESTIGATION OF MECHANISM OF POTENTIAL AIRCRAFT FUEL TANK VENT FIRES AND EXPLOSIONS CAUSED BY ATMOSPHERIC ELECTRICITY

Progress Report No. 1
December 26, 1961

LOCKHEED AIRCRAFT CORPORATION
CALIFORNIA DIVISION • BURBANK, CALIFORNIA, USA

INVESTIGATION OF MECHANISMS OF POTENTIAL AIRCRAFT FUEL TANK VENT FIRES AND EXPLOSIONS CAUSED BY ATMOSPHERIC ELECTRICITY

NASA RESEARCH PROJECT NO. NASAr-59

Progress Report No. 1

For Quarter Ending
5 December 1961

A research project jointly supported by the
National Aeronautics and Space Administration
and the Federal Aviation Agency

SUMMARY

The nature of the potential fuel tank vent fire and explosion hazard is discussed in relation to present vent exit design practice, available knowledge of atmospheric electricity as a source of ignition energy, and the vent system vapor space environment. Flammable mixtures and possible ignition sources may occur simultaneously as a rare phenomena according to existing knowledge. There is a need to extend the state of science in order to make possible vent design which is aimed specifically at minimizing fire and explosion hazards.

In the experimental investigation being continued, data will be obtained on

(a) Fuel-air mixture profiles at the vent exit;
(b) Shock wave energy densities in the near field of a lightning strike;
(c) Flame quenching in a high velocity gas stream; and
(d) Ignition potential of atmospheric electrical phenomena.

Fuel tank vents, for the purposes of the present investigation, are considered to be configured as one of the following:

(a) Masts which extend across stream lines and which discharge vapors into the free stream;
(b) Masts which discharge rearward into a generated wake such as by a wing; and
(c) Flush vents which discharge into a surface boundary layer.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION I

INTRODUCTION

This first Progress Report covers the work accomplished during the period 5 September 1961 to 5 December 1961 on NASA Research Project No. NASr-59 entitled "Investigation of Mechanisms of Potential Aircraft Fuel Tank Vent Fires and Explosions Caused by Atmospheric Electricity." The research is being conducted by a team consisting of Dynamic Science Corporation, South Pasadena, California; Lockheed-California Company, Burbank, California; and Lightning & Transients Research Institute, Minneapolis, Minnesota.

The effort thus far has been placed upon (1) Critical Evaluation of the Problem, which includes a review of present fuel vent design practices, establishing typical tank and vent environmental conditions, review of some of the lightning strike statistics and properties of lightning and atmospheric electric fields, review of the ignition processes as applied to the problem, and a look at some present protective measures; and (2) Planning of the Initial Test Phases based upon the above evaluation.

A letter was sent out on November 22, 1961 to 40 aircraft companies advising them of the start of this program and of our initial plans and objectives, and requesting their comments and contributions to this industry wide problem.

SECTION II

DISCUSSION OF THE PROBLEM

Fuel tanks on aircraft are vented to the atmosphere to prevent excessive pressure differences from occurring between the internal and external surfaces of the tank. As the aircraft changes altitude there is a flow either out of or into the tank, depending upon whether the aircraft is ascending or descending or, more exactly, whether the internal pressure is higher or lower than the pressure at the vent outlet. As a result of this "breathing" process, it is conceivable that flammable fuel-air mixtures may exist within the vent line and within the tank itself. The occurrence of flammable mixtures within the tank-vent system would be strongly dependent on the flight history of the aircraft, changes in external ambient pressure and on the fuel volatility. The existence of such flammable mixtures thus requires the proper combination of several variables, and it cannot be accurately predicted whether such mixtures will actually exist in any given situation or, if they do exist, when they will occur and how long they will remain.

The existence of a flammable mixture is, by itself, not a hazardous situation unless sources of ignition are also present and, in addition, unless a flame can be initiated and propagated into the fuel tank. Even under these conditions, the flame must reach a mixture within the fuel tank capable of producing a significant temperature and pressure rise before a serious situation exists.

One possible ignition source, arising from events external to the aircraft, is due to atmospheric electrical phenomena such as lightning streamers and corona discharges. Such discharges can be shown, under carefully controlled laboratory conditions, to contain sufficient energy to ignite suitable fuel-air mixtures. A more detailed discussion of the relationship of ignition energy to mixture composition will be given later in this report.

Inasmuch as the sources of flammable mixtures and of ignition exist, it must be assumed in the absence of other knowledge that a hazardous condition may also exist. The fact that the flammable mixtures and ignition sources

exist only as transients and may, therefore, not exist simultaneously, greatly minimizes the hazard but may not completely eliminate the potential of fire from these sources. For this reason, aircraft designers have chosen vent designs and vent locations based on the best knowledge available to them to further reduce the possibility of fire originating at the fuel vent as a result of atmospheric electrical phenomena. Unfortunately, all of the scientific data needed by designers is not available and some of the results of recent research on ignition, quenching and flame propagation are not yet in a form which is useful to the designer. It is the objective of this research investigation, of which this is the first report, to perform research directed toward supplying some of the necessary information required to minimize the possibility of fuel vent fires due to atmospheric electrical phenomena. It is the objective of this report to summarize some of the important elements of the problem and to highlight those research areas requiring the most attention. In order to accomplish the latter objective, this report summarizes current concepts of vent configuration and location as well as current knowledge pertinent to the nature of the atmospheric electrical phenomena, ignition and flame propagation and flame quenching. Important blanks in the current status of knowledge are emphasized and serve as a guide for later portions of the program.

There are three fundamental techniques which can be used to minimize the possibility of explosions resulting from fuel vent fires due to atmospheric electrical phenomena and these are:

1. Elimination of discharges capable of producing ignition in the vicinity of the fuel vent.
2. Elimination of combustible mixtures in and around the fuel vent exit.
3. Elimination of the possibility of flame propagation into the vent line.

These techniques, either alone or in combination, would greatly minimize, and possibly eliminate the potential hazard of fires from the circumstances being considered in this investigation.

SECTION III

FUEL VENT EXIT CONFIGURATION AND LOCATION

The selection of a vent configuration and location depends upon a number of factors, all of which are important for efficient and safe operation of the aircraft. The vent exit configuration must be designed to handle the expected flows into and out of the fuel tank for all possible flight plans and maneuvers of the aircraft at all conditions of the ambient atmosphere which the aircraft will encounter during its flight. In some cases it must also be able to handle fueling overflow in event of failed fuel valves without overpressuring the tank. At the same time, the vent exit must be compatible with the external aerodynamics of the aircraft and, hence, must be designed to minimize drag and possible interference effects. The vent design and location must also include considerations which minimize the possibility of electrical discharges occurring at or near the vent exit as a result of lightning strikes, or as a result of the vent acting as a source of secondary discharges such as streamers and coronas. In addition, the vent location is chosen to prevent the venting of fuel into possible ignition sources such as the engine and to prevent the venting of fuel at such locations where fuel could enter the cabin, either directly or through the cabin air conditioning system. In most cases an effort is also made to locate the vent at a position which minimizes the length of the piping between the fuel tank and the vent exit. These and other practical considerations must be taken into account in the design and location of fuel tank vents.

Inasmuch as the design and location of the vent system involves many parameters which depend on the aircraft configuration, these vents assume many different appearances and occur in varied locations for different aircraft. Some typical vent exit configurations and locations are illustrated in Figure 1. These configurations and locations are by no means complete but are presented only as representative and serve as an orientation to the physical situation which may exist near the fuel vent exit.

In order to understand the phenomena which may occur in the vicinity of the fuel vent exit and in order to limit the number of experimental configurations which may be explored, it was desirable to determine whether these varied configurations and locations could be generalized in terms of the flow fields which exist near the vent exit. A close examination of a large number of configurations and locations indicated that all of them seemed to be variations of three principal classes. These classes are:

1. Mast discharging into a wake
2. Mast discharging into a free stream
3. Flush vent discharging into a boundary layer.

These three vent classes, shown schematically in Figure 2, differ not only in terms of their interaction with the electrical environment which may exist around them and which also depends on the aircraft configuration, but also in terms of the aerodynamic field into which fuel vapor is discharged. These three classes have been chosen as the basic configurations for the experimental program to investigate the electrical and combustible environment in the vicinity of a fuel tank vent exit.

SECTION IV

FLOW PARAMETERS

Two different flow fields are important in the evaluation of the fuel-air mixture which may exist in and around the fuel tank vent exit. The first of these is the flow of the air around the vent which depends on the aircraft speed and vent location, while the second is the flow within the vent itself which depends on the tank volume, quantity and type of fuel in the tank, fuel temperature, rate of change of external pressure, the vent geometry, and the ambient altitude. The nature of the fuel-air mixture at the vent exit depends to a large degree on whether the aircraft is ascending or descending; that is, whether the external ambient pressure is decreasing or increasing. In assessing the possible existence of a hazardous condition at the vent exit it would appear that the climb condition is the most serious. It is during climb, while the external ambient pressure is decreasing, that the fuel tank is discharging fuel vapor either by itself or mixed with air. Hence at this time a flammable mixture may exist in or near the vent exit. During descent, while the external ambient pressure is increasing, ambient air is flowing into the vent, and it appears quite reasonable that the portion of the vent near the exit is reasonably free of fuel. /This observation is not necessarily true for the fuel tank since the admission of air may produce a flammable mixture where none existed before.

In order to evaluate quantitatively the conditions existing at the vent outlet, a theoretical study to establish flow parameters for an experimental program was initiated. The study considered many variables, of which vent exit velocity, mass flow and fuel-air ratio surrounding the exit were established as being most significant for further investigation. It is not unlikely, for this reason, that the greatest hazard may exist during a climb following a descent. During this condition air has been admitted to the tank during descent and a flammable mixture may be discharged during the subsequent ascent.

Computations of vent exit velocity were made for typical airplanes operating at maximum rate of climb. The venting occurs in two definite regimes, that prior to reaching fuel boiling altitude and that above fuel boiling altitude.

Below fuel boiling altitude the vent rate was obtained by applying the equation of state to the tank vapor space and obtaining the following equation for vent exit velocity:

$$U_v = \left(\frac{V}{A_v}\right)\left(\frac{dp/dh}{P}\right)\left(R/C\right)$$

where

U_v = vent exit flow velocity
V = tank vapor volume
A_v = vent exit area
dp/dh = change of pressure with altitude
P = tank pressure (assumed = amb. pressure)
R/C = rate of climb.

This equation shows that maximum vent velocity is obtained at maximum rate of climb when the vented volume is maximum. Thus, where in most cases the vent rate will be based on full fuel tanks with expansion space venting plus air evolution, the maximum is obtained when the tank is nearly empty. Figure 3 illustrates the above mentioned vent velocities as referenced to airplane climb speed to give the vent velocity ratio, U_v/U_o, and shows the increase in vent rate as the vented volume increases from expansion space only, to expansion space plus air evolution, to "empty tank." For purposes of establishing test ranges of the velocity ratio, the altitude variation of "empty tank" vent rates were computed for six aircraft and are shown in Figure 4. Ten curves are shown because some aircraft have separate vents for each tank. The following table summarizes some of the aerodynamic conditions which accompany the sea level maximum velocity ratios.

Aircraft Model	Aircraft Speed U_o knots	Boundary Layer Thickness at Vent - inches	Reynolds Number at Vent $Re_{(x)} \times 10^{-6}$	Maximum U_v/U_o
A	160	1.7	18	0.045
B	310	3.7	110	0.017
C_1	147	0.6	4.7	0.125
C_2	147	1.9	19	0.0125
D	152	1.0	8.7	0.09
E_1	190	0.9	11	0.16
E_2	190	0.9	11	0.47
F_1	190	0.9	11	0.092
F_2	190	0.9	11	0.029

The calculation of vent velocity ratio for altitudes above the fuel boiling altitude is an iterative process using the vent system pressure drop characteristic and the data on fuel percent weight loss versus pressure on the fuel surface. This calculation takes into account the increase in tank pressure during the climb as fuel boiling proceeds. Shown in Figure 5 is a comparison of the non-boiling and boiling velocity ratios for one tank system of aircraft "A", which uses 115/145 fuel. To show a maximum velocity ratio situation, Figure 5 assumes the tank is individually vented, whereas airplane "A" actually utilizes a manifolded system having a lower exit velocity (compare the non-boiling rate with Figure 4). For JP-4 fueled aircraft and the associated higher boiling altitude, there is less difference between non-boiling and boiling vent rate as indicated in Figure 6.

In computing the nature of the combustible environment at the vent exit, the vent mass flow as a function of altitude is an important variable. This parameter can be computed from the equation:

$$W = \left(\frac{V}{RT_v}\right)\left(\frac{dp}{dh}\right)\left(R/C\right)\left(\frac{1 + F/A}{1/M_a + \frac{F/A}{M_f}}\right)$$

where F/A = 16 Fuel/16 Air

R = universal gas constant (=1545)

T_v = vent mixture temperature ^{o}R

M_a = Mol. Weight of Air

M_f = Mol. Weight of Fuel

Other terms as before.

The effect of fuel/air ratio of the mixture upon vent exit mass flow rate is shown for one airplane in Figure 3.

Another important factor determining the nature of the effluent from a fuel vent is the nature of the mixture in the fuel tank, particularly that portion of the mixture which is involved in the flow through the vent. Unfortunately, the homogenous, equilibrium mixture is the only one which can be calculated with confidence, and hence, where experimental data are not available, must be used to determine the composition of the fuel vent effluent. The saturated fuel-air ratio in the tank vapor space can be calculated from the following equation:

$$F/A = M_f/M_a \left(\frac{P_f}{P_{amb} - P_f}\right)$$

where

M_f = molecular weight of fuel

M_a = molecular weight of air

P_f = vapor pressure of fuel

P_{amb} = ambient atmospheric pressure.

Figures 7 and 8 give computed values of the tank fuel/air ratio along the climb path of aircraft "A" and "E" respectively, for different assumed tank temperatures. It is seen that unless the fuel is initially cold, or unless the temperature follows closely the altitude temperature during climb, the mixture is normally too rich to be flammable.

Unfortunately, such calculations cannot be used as more than a guide to judge the safety of the tank from explosion since non-equilibrium conditions may exist which produce flammable vapor-air mixtures, and sloshing of fuel may produce mist-air mixtures capable of explosion. Experimentally it has been shown in tests conducted by the British that equilibrium conditions do not necessarily exist in a fuel tank which breathes as a result of ascent and descent. One experimental result from their study is illustrated in Figure 9, which shows a flight plan in terms of altitude as a function of time and the measured fuel-air ratios as a function of time. It is seen that flammable mixtures did occur in these tests although the equilibrium fuel-air ratio would have been richer than the flammable zone for the fuel used under the conditions of the test.

Inasmuch as flammable mixture may exist in the fuel tank under some conditions, the most desirable approach toward reducing fires due to atmospheric electricity in the vicinity of fuel vents must be directed toward eliminating the possibility of flame propagation into the tank.

SECTION V

ATMOSPHERIC ELECTRICITY *

The atmospheric electrical environment represents the principal ignition source in the problem under consideration. In general, the energy available in a lightning strike is many orders of magnitude greater than the usual energy sources used in ignition research. The lightning induced corona discharge streamer probably approaches closest to laboratory ignition tests. Newman and coworkers have shown that the lightning induced corona streamer discharges associated with aircraft surfaces are capable of igniting fuel-air mixtures. Here, as in other ignition problems discussed in the next section, the important feature is the relationship between the ignition energy and the properties of the combustible mixture. The discussion presented in this section summarizes a small part of the lightning research pertinent to the fuel vent problem.

The occurrence of lightning in terms of geophysical parameters such as geographic location and altitude is difficult to evaluate since the observations are incomplete and, at best, the results are statistical in nature. The important question in terms of the fuel vent problem is whether an appreciable percentage of lightning strikes occur in that portion of the atmosphere through which aircraft operate and where, at least in principle, combustible mixtures may exist in and around fuel vents. A study made by Lightning and Transients Research Institute on the observation of lightning strikes indicates that, of the observed strikes, over 90 percent of the strikes were observed in the ambient atmosphere temperatures ranges, $-10^{\circ}C + 10^{\circ}C$, and that 65 percent of the strikes were observed in the range $0^{\circ}C$ to $+ 5^{\circ}C$. The data upon which these observations were made are shown in Figure 10. While it is true that the results were based on a necessarily limited number of observations, the results are the only ones available which can be used to relate the incidence of lightning with a property, temperature, which determines the equilibrium vapor pressure of the fuel and, hence, the possible existence of a flammable mixture.

* A detailed analysis of more recent data and additional studies in progress of LTRI on lightning channel characteristics is in preparation under this program for a more comprehensive treatment of the electrical environment.

A similar study was made for the observation of lightning strikes as a function of altitude. These results are also shown in Figure 10. Included in Figure 10 are some data based on a much smaller number of observations reported by the Royal Dutch Airlines. Inasmuch as altitude and temperature are related in the atmosphere, these two figures are not necessarily independent.

As much as possible, the probable location of lightning strikes on the aircraft guide the vent placement, and since strikes usually occur at sharp edges or proturberances, it is usual practice to avoid placing vents near such surfaces and to design the vent so that it does not produce such a surface. Unfortunately, the actual sites which meet all of the requirements for fuel vent location are limited and it becomes a difficult task to determine an optimum location.

Experimental data have been obtained which indicate the relative locations of lightning strikes. These data are summarized in Table I. In terms of the major structural features of the aircraft, a substantial portion of the strikes occur at the fuselage nose and on the wings with the wing tips being particularly vulnerable. Since the wings are used to carry the fuel tanks in most commercial aircraft, it is necessary to locate the fuel vent at some portion of the wing in a relatively strike-free position. At first glance it would appear that a position remote from the wing tip would be desirable. It is found, however, that for propeller aircraft the area behind the propeller is swept by discharges directed at the blade tips, and in jet aircraft the jet pods are susceptible.

In the aft portions of the aircraft, sharp edged fins and stabilizers are subject to strikes as are small protuberances such as the antenna, etc. Much work has been done to protect individual parts of the aircraft from damage by lightning, but this does not necessarily remove the ignition hazard if a vent is located in the vicinity and a strike can occur even without structural damage.

A map of equipotential lines about an aircraft model can be obtained in laboratory tests with a simulated lightning strike.

TABLE I

SUMMARY OF DATA ON DAMAGE LOCATION AND AREAS OF VULNERABILITY OF LIGHTNING STRIKES

Location	Flight Data Accumulated by Lightning & Transients Research Institute (275 strikes) ①	Flight Data Accumulated by Royal Dutch Airlines (21 strikes) ②	Areas of Vulnerability Douglas DC-8 Model Tests ③	Areas of Vulnerability Boeing 707 Model Tests ④
Fuselage Nose	11%	21%	37%	33%
Wing & Aileron	21%	29%	19%	20%
Elevator & Horizontal Stabilizer	13%	19%	22%	16%
Rudder & Vertical Fin	9%	11%	16%	16%
Jet Pods			3%	8%
Propeller	7%	3%		
Antenna	27%	8%		
Tail Cone			3%	4%
Miscellaneous	12%	9%		3%

① NACA TN 4326

② Lightning & Static Discharge Report with Regard to KLM Airplanes 1-22-53 TW-1186 Report 2

③ Aircraft Protection from Atmospheric Electrical Hazards Interim Report 4 Jan. - Mar. 1958 Report 347, Lightning & Transients Research Institute

④ Boeing Aircraft Document No. D6-1728

The points of high potential gradients which can give rise to secondary discharges produced as a result of the original lightning strike can thus be determined. Such maps have been made at Lightning and Transients Research Institute.

The energies involved in a lightning strike are overwhelming compared to those usually studied in ignition research. This fact is one of the principal reasons for the need of additional research information. The lightning channel in the immediate vicinity of the aircraft contains energies in excess of thousands of joules, while most minimum ignition studies involve energies in the millijoule range. It is further estimated that the total average charge transfer within a lightning strike is of the order of 20-30 coulombs, with an occasional charge transfer of over 600 coulombs.

Lightning induced corona streamers of millijoule energies may occur even with strokes far away from the fuel vents; however, in the case of nearby strokes, the high energy may alter the concepts of ignitability and flammability. In addition, the strong pressure pulse produced by the discharge may by itself be a strong factor in ignition and flame propagation.

In terms of information useful to the fuel vent designer, it is necessary to locate the vent exit in a region with a low probability for lightning strikes and in a region where potential buildup from a lightning strike is low to minimize the occurrence of secondary discharge of that location. While some idea of favorable locations can be deduced from existing data, model tests which accurately simulate the aircraft configuration may also be desirable.

SECTION VI
IGNITION

It has been assumed during this preliminary examination of the fuel vent fire problem that the most serious condition at the vent exit exists during climb when fuel or fuel and air are flowing from the fuel tank through the vent. As the mixture leaves the vent it mixes with the ambient air, and undergoes dilution. From the vent exit outward, therefore, all fuel-air ratios are leaner than the vent effluent. Whether or not ignition can occur depends on the ignition energy available at various existing fuel-air ratios.

The discussion of the ignition model can be illustrated by means of a jet discharging into a free stream, a configuration which is analogous to the case of a vent mast discharging into a free stream. Considerable data exist for the case where the jet velocity exceeds the free stream velocity and it has been shown that temperature and concentration diffuse at about the same rates. While actual aircraft vent conditions are reversed in the sense that the jet velocity is less than the free stream velocity, it is convenient at this time for illustration purposes only to use a mixing profile already in literature. The quantitative values will not correspond to the actual case but the general discussion will illustrate the technique to be used in evaluating the test data to be obtained in this program.

A typical profile is shown in Figure 11 for the case of $\frac{U_v}{U_o} = 4.0$.

Having established an arbitrary fuel-air mixture profile, it is desired to know what is required to produce a flame. The precise answer to this question is not known, most ignition work having been done with homogeneous mixtures, but it is of interest to determine what can be suggested from existing information. Let us assume that the effluent gas is a propane-air mixture at ambient sea-level temperature and pressure and with an equivalence ratio in the vent of $\psi_v = 2.5$ the rich limit value for propane. It is now possible to draw an ignition energy map based on the following data. The variation of ignition energy with ψ for

propane is given in Figure 12. For each value of ψ in Figure 11 (based on ψ_v = 2.5) there is a corresponding value of ignition energy from Figure 12. The ignition energy map would appear as illustrated in Figure 13, which is essentially a cross-plot of Figures 11 and 12. The ignition energy map in Figure 13 has an interesting characteristic. Since there is an optimum fuel-air ratio for ignition as seen by the minimum in the curve of Figure 12, the ignition energy profile along the jet axis, for example, decrease as the distance from the jet increases and then increases again as the distance from the jet continues to increase. For a given ignition energy, then, there is actually an envelope which, at least as a first approximation, can be ignited. As the energy of the source increases, the size of this envelope also increases. It is also pertinent for the particular configuration chosen that the envelope approaches quite close to the tube producing the jet at the sides of the jet stream.

Since the initial concentration of fuel in the jet effluent was chosen within the flammable range it is conceivable that a flame could propagate into the jet if the velocity relationships are proper. Under conditions of maximum vent exit velocity the flame may not be capable of flashing back into the vent. However, if the vent velocity decreases due, for example, to a change in the climb rate, flame propagation might occur. It is evident that a hazardous condition only occurs if a number of events occur in the proper sequence at the proper time.

The preceding discussion has been presented to describe a possible model for an ignition process at a fuel vent exit. Until a quantitative calculation is made for the conditions actually existing in the fuel vent problem it is not possible to assess the probability of ignition. Such calculations as well as experiments to determine the combustible environment will be conducted in the program. It is important to determine these parameters since the effectiveness of dilution techniques will depend upon the ability of using dilution to minimize ignition probability. It is quite possible, for example, that dilution near the edges of the fuel vent could be extremely effective with minimum quantities of dilution air if it can be shown that the vent boundary is the most likely source

of discharges. Experiments to determine the likely location of discharges near a vent exit are also planned.

It is relevant at this point to summarize briefly some of the known facts concerning electrical ignition. Unfortunately, for the purposes of this study, much of the data have been obtained under rather idealized laboratory conditions and therefore can be used only in a qualitative sense.

Minimum ignition energies for spark ignition are usually measured by discharging a known energy as a spark into a quiescent, homogeneous fuel-oxidant mixture at a given temperature and pressure. The energy of the spark is altered until a critical value is reached separating ignition from non-ignition. The usual criterion for ignition is that a flame is produced which is self-sustaining and propagates away from the source of ignition. In this sense ignition and flame propagation are coupled since it is entirely possible and has, in fact, been shown experimentally that chemical reactions and, in some cases actual flames, originate at energies below the minimum ignition energy. Such reactions and/or flames are not stable and soon vanish. The ignition energy as measured experimentally depends upon the electrode spacing and geometry as shown in Figure 14. The value of the ignition energy at spacings where the curve has leveled off is usually taken as the minimum ignition energy. When flanged electrodes are used the sharp break in the curve can be used as a measure of quenching distance as shown.

The ignition energy varies with fuel-air ratio as has been shown in Figure 12 for propane. Unlike other flame properties for hydrocarbons which show maxima or minima at roughly the same equivalence ratios, the minimum in the fuel-air ratio curve shifts to richer mixtures as the molecular weight of the hydrocarbon increases. A widely accepted explanation for this shift has not yet been advanced. Because of the shift, it is difficult to predict the ignition energy of mixtures since the various components of the mixture are at different individual equivalence ratios.

A number of important questions remain unanswered, however, particularly for the case where large ignition energies are involved. Re-examination of

the propane data in Figure 12 indicate that an ignition energy of approximately 10 millijoule is required to ignite a mixture at the lean limit of flame propagation. What happens if a high energy is applied to a leaner mixture? Presumably, if the energy is high enough, a chemical reaction is initiated and it is possible that a transient over-driven flame may be produced. It is not known how long such a flame would propagate for a given energy. Presumably, since such a flame should lose energy at a faster rate than energy is generated within the flame, it should eventually be extinguished but if such a flame can propagate into a more flammable mixture before it has lost its excess energy, it could ignite such a mixture. If such is the case the normal concepts of flammability and ignitability do not apply for situations where large excess energy is available for ignition.

Inasmuch as the consideration of lightning as a source of ignition involves energies considerably above minimum ignition energy, an estimate of the distance necessary to dissipate a given quantity of excess energy is useful. No theory has yet been advanced to calculate this distance. In order to obtain an order of magnitude idea of the energy dissipation length an estimate has been made based on the rate of energy dissipation determined from quenching experiments and theory. Examination of the energy loss equations for the case of hydrocarbon flame indicates that the order of $\frac{10^{-3}}{D^2}$ joules are dissipated per centimeter of flame travel where D is the tube diameter. This value does not include the energy loss within the flame itself as it attempts to reach an equilibrium condition. For a 1 cm tube, an excess energy of 1 joule would require 10^3 cm or about 30 feet. The result could easily be in error by an order of magnitude since an over-driven flame loses energy as a result of non-equilibrium processes within the flame itself as well as to the walls of the tube. Nevertheless, the indications are that large excesses of energy could drive a presumably non-propagating flame for relatively large distances.

A major lack in our information concerning ignition is the effect of large energies on the probability of ignition and on the conditions necessary to remove the excess energy. These studies will be pursued in the present program. It is

in fact, necessary to examine the mechanism of the ignition process with particular reference to the conditions resulting from atmospheric electricity in the vicinity of fuel vents before a definitive approach can be made toward an understanding of the mechanism of ignition and the associated hazards.

Another aspect of ignition which has not received attention is associated with the strong pressure wave which accompanies a lightning strike. These pressure waves can act as ignition sources in themselves and can also induce flows into the vent which would normally not exist. It is also characteristic of ignition by shock waves that a detonation rather than a deflagration is produced so that the associated damage could be much greater than would be expected in the absense of the pressure wave.

An estimate of the ignition capabilities of shock waves may be obtained from the following data: (Ref. NACA TR 1300, page 111)

Properties of Shock Waves

Ratio of pressure	Velocity-Ft/sec	Temp Behind* the Shock - °F
2	1,483	145
5	2,290	408
10	3,209	810
50	7,050	3,610
100	9,910	6,490
1000	30,200	33,900
2000	42,300	51,700

* Initial temperature is 32°F.

It is apparent that shock waves with a pressure ratio as low as 5 approach the ignition temperature of many substances and that a shock wave with a pressure ratio of 10 produces a temperature rise above the ignition temperature of most aviation fuels. It has been shown, for example, that methane-oxygen mixtures could be ignited by shock waves in which the calculated temperature was of the order of 450°F. The investigation of the pressure fields associated with a lightning strike is an important part of the present investigation.

SECTION VII

FLAME ARRESTORS

One method often suggested as a means of preventing explosions from ignition at fuel vent exits is the use of flame arrestors. The flame arrestor is designed to prevent a flame from propagating into the fuel tank by quenching the flame. The quenching action of a flame arrestor depends on the abstraction of sufficient heat from the flame to prevent self propagation. Since the heat abstraction by the tube walls depends on the tube diameter, for each mixture and set of initial conditions there is a critical value of the channel dimensions below which flame propagation cannot occur. These critical dimensions are called the quenching distance. A flame arrestor consists of a collection of channels with dimensions smaller than the quenching dimensions.

Quenching distances are determined experimentally in several ways. The most commonly used method consists of establishing a Bunsen type flame at the end of the channel; when the flow is suddenly interrupted the flame may or may not flash back into the channel. The channel dimensions separating propagation from non-propagation are called the quenching dimensions. In another technique a flame is initiated in a quiescent mixture in a large channel and propagates toward a smaller channel or, in some cases, an orifice. The dimensions separating propagation into the smaller channel or orifice from non-propagation are the quenching dimensions. It is noteworthy that the same results are obtained whether an orifice or a long channel are used. Other techniques such as electrode spacing as discussed previously and derived values from other flame propagation properties have also been used. In all these experiments a steady-state flame is first established and the flame approaches the quenching surface at very low velocities, usually no greater than the flame speed, which for hydrocarbons is of the order of two feet per second.

A typical curve of quenching distance for plane parallel plates is shown in Figure 15 for propane as a function of pressure. For most hydrocarbon-air mixtures the relationship

$$D \propto {}^{1}/_{P^2}$$

is approximately true.

A reasonably satisfactory theory for calculating quenching distance has been developed by assuming that the flame is extinguished when the flame temperature is reduced to some critical value. To obtain the quenching distance it is further assumed that the heat released by the flame is equal to the heat loss to the channel walls at the critical condition. The equation has the form:

$$D^2 = \frac{FG \lambda_r X_f}{C_{p,r} W}$$

where

D	=	quenching distance
F	=	fraction of normal heat release retained by the flame, for hydrocarbons about 0.75
G	=	channel geometry factor
λ_r	=	thermal conductivity in reaction zone
X_f	=	mole faction of fuel in mixture
$C_{p,r}$	=	mean specific heat in reaction zone
W	=	flame reaction role

The geometric factor G can be assigned a value of 1 for infinite plane parrallel plates. From heat transfer theory it can be shown that if

$$G_p = 1$$

$$G_c = 32/12$$

$$G_r = \left[1 - 0.3\ ({}^{dr}/br) - 0.0470\ ({}^{dr}/br)^2\right]^{-2}$$

$$G_a = \frac{32}{12}\left[1 + (^a/da)^2 + \frac{1 - (^a/da)^2}{\log_e(^a/da)}\right]^{-1}$$

$$G_e = \frac{32}{12}\left[\tfrac{1}{2}\left\{1 + (^{de}/be)^2\right\}\right]$$

$$G_t = 80/12$$

where

subscripts

p = plane parallel plates

c = cylinder

r = rectangle: d_r = width, b_r = length

a = annulus: d_a = outside diameter, a = inside diameter

e = ellipse: d_e = minor axis, b_e = major axis

t = equilateral triangle

These relationships can be used to evaluate the effectiveness of various geometries. The annulus is particularly interesting since the introduction of a very small center body has a very strong effect in reducing the quenching outer diameter.

In applying these quenching dimensions obtained under carefully controlled laboratory conditions to the design of practical flame arrestors, a number of problems arise which may render the flame arrestor inoperative if not considered. One of these problems is that the flame arrestor walls may heat up as a result of the heat transfer from a flame established at the inlet to the arrestor. In the laboratory experiments the channel walls are usually kept at the same tempertture as the gaseous mixture. The thermal theory of quenching can be extended to estimate the effects of wall temperature, assuming for the first case that the mixture temperature is not affected.

Extension of the quenching theory results in an equation of the form

$$d_o^2 - d^2 = (T_w - T_o)\ \left(\frac{G\chi}{q}\right)$$

where

d_o = quenching distance at $T_w = T_o$

T_w = wall temperature

χ = thermal diffusivity

q = rate of temperature rise caused by chemical reaction

and

$$\frac{d_o^2}{d^2} = \frac{1}{1 + \dfrac{T_o - T_w}{(F/E_p)\ X_f \triangle H}} \approx \frac{1}{1 - \dfrac{T_w - T_o}{0.75(T_f - T_o)}}$$

For qualitative comparison, assuming $T_o = 300^oK$ and $T_f = 2000^oK$, we get

T_w ^oK	$\frac{d_o}{d}$
400	1.04
600	1.15
1000	1.48
1275	∞

The results shown above are only approximate but the trend is evident and a flame arrestor designed for a cold wall could easily be ineffective if the wall becomes hot. The ratios shown are actually too low since the gas itself would be heated in the process. The heat release term is an exponential function of T_f which varies roughly linearly with T_o and hence, heating of the walls and gas could easily lead to large errors in the channel dimensions.

Another factor which is often ignored in the design of flame arrestors is the effect of gas velocity. It has already been mentioned that the laboratory measurements are based on very low velocities. A flame about to be quenched in a channel of quenching dimensions loses about 10^{-2} calories when travelling approximately .1 cm at about 1 foot per second. To lose the same amount of heat in a stream flowing with the flame at 100 feet per second would require 10 cm. It is thus possible that a flame can be blown through a channel if the channel is too short. Actually no theoretical or experimental data exist for quenching in high velocity gas streams and the values given above are at best crude estimates but serve to indicate general trends.

SECTION VIII

EXPERIMENTAL PROGRAM

A. GENERAL

The first phase of test work is designed to obtain data not now available on the mixing of vent vapors with a moving airstream for vent configurations which fall into the three general categories shown in Figure 2. These results will be used in planning ignition and combustion tests of Phase II.

Initial tests will be carried out with a model representing Figure "C" of Figure 2. The model (See Figure 16) will be set up in the Lockheed Power Plant Laboratory wind tunnel which is capable of providing a 10 ft. diameter air stream at speeds up to about 120 knots. Various vent mixtures will be fed into a controlled surface boundary layer and, by means of a sampling probe having 3-dimensional travel, a map of fuel-air ratio in the vicinity of the vent will be established.

For the first tests, where it is desired to obtain fundamental mixing data, bottled butane gas will be used in order to have better control of vent mixtures, as well as a simpler fuel feed and control system. Results will be verified with vapors from aviation type fuels. The following range of variables will be examined.

Vent fuel/air ratio: lower flammable limit to pure vapor
Vent boundary layer thickness/vent diameter ratio: 0 to 3
Vent temperature/stream temperature ratio: 0.75 to 1.5
Vent exit velocity/stream velocity ratio: 0 to 0.6

In addition, since the ambient pressure cannot be varied in the wind tunnel, the effect of variation in the fuel vapor pressure/ambient pressure ratio will be checked by use of different fuels.

Fabrication of the model and tunnel test structure has been initiated.

B. SAMPLE SYSTEM

1. Probe and Control System

Two conditions which have been placed on the probe which samples the vented mixture are, (1) the probe must be able to sample within flame quenching distance of the model surface, and (2) it must sample isokinetically (inlet velocity = stream velocity in front of the probe) so as to collect a representative sample.

Figure 15 indicates that at ambient pressure the quenching distance is probably in the order of 0.1 inch. Therefore, the probe will be, as shown in Figure 17, made from a stock size hypodermic needle having 0.05" outside diameter. Two general methods of isokinetic sampling which are generally used (ref. A Gardograph 47 "Gas Sampling and Chemical Analysis in Combustion Processes", 1961, section B) are the null-probe method and the volumetric method. The null-probe method requires a probe which references the static pressure inside the probe to that outside the probe, and isokinetic conditions are reached when the pressure difference is zero. This method requires calibration to account for geometry effects on the internal pressure measurement which, in turn, is dependent upon the unknown mixture ratio at the probe entrance. Further, the null-probe would be too bulky to be compatible with the above discussed size limitation.

It has been decided, therefore, to use the volumetric method in the following manner (refer to schematic of system in Figure 17). With the sample control value closed the probe total pressure is read from the manometer, which with the stream static pressure gives the stream Mach number (if it is assumed that air only is flowing). Then the sample valve is opened allowing the sample suction pump to establish probe flow which enables measurement of sample temperature inside the probe. Then with a known probe capture area, the stream tube mass flow in front of the probe is determined. This value of flow rate is set on the sample rotameter to give isokinetic probe conditions.

The apparent error in the above procedure is obviously the assumption that air only is flowing into the probe and the meter being set for the corresponding mass flow rate. However, it has been shown by analysis of the equations of flow at the probe and at the rotameter that the system will be self compensating by virtue of the fact that the density of material used in the rotameter float is sufficiently large. That is, we expect to be able to assume only air is flowing at the probe and be able to set the isokinetic mass flow rate at the meter (with negligible error) even though pure vapor is actually coming into the probe. A nomographic-type probe flow chart (which also includes meter pressure and temperature correction factor) has been prepared to simplify the flow setting process.

Another feature designed into the system is that since the analyzer requires the use of variable amounts of dilution air depending upon sample concentration (see below), the sample suction pump has been selected to maintain choked conditions at the sample control valve at all times. Thus, control setting variation of the dilution air will not effect the sample meter setting.

The sample suction pump has been obtained, and buildup of a sample system control panel has been initiated.

2. Gas Analyzer

A Perkin-Elmer Model 213B Hydrocarbon Detector (Figure 18) has been obtained for measurement of the fuel-air ratios. The instrument utilizes the principle of hydrogen flame ionization for the detection of gaseous hydrocarbons. The test gas sample is introduced into the Model 213B under pressure, metered, mixed with hydrogen, and burned in an atmosphere of air in an enclosed chamber. Within the chamber a 300 volt D-C potential exists between the flame jet and an electrode. Hydrocarbons in the sample are ionized by the flame causing a current to flow which is proportional to the carbon content of the sample gas. The resultant current is read on a meter or an externally connected recorder. The hydrocarbon concentration in the sample gas can be read directly on the meter by calibrating the instrument with a gas of known hydrocarbon concentration.

Because the maximum hydrocarbon concentration of about 3% by volume that can be measured directly by the instrument is less than that anticipated to be sampled near the vent, where the concentration may be as high as 100%, the primary gas sample will require dilution. This will be done accurately by use of the flow system shown in Figure 17.

3. Traverse Mechanism

To facilitate positioning of the gas sampling probe without the necessity of shutting down the tunnel between samplings, an accurate three dimensional, remote controlled traverse mechanism shown in Figure 19 has been designed and fabricated. Movement and read out of the probe position is done electrically through the control circuit shown in Figure 20. Linear potentiometers driven by the traversing screws have been individually calibrated with respect to the three dimensional position of the probe against a digital potentiometer in a null indicating bridge circuit.

The probe attached to the vertical arm of mechanism can be remotely repositioned with respect to an initial predetermined starting point with an accuracy of ± 0.005" in the vertical, ± 0.010" in the lateral, and ± 0.012" in the logitudinal directions through full travel distances of 4.9, 10.8, and 8.8 inches respectively.

CONCLUSIONS

1. The venting of aircraft fuel tanks is currently accomplished in the aerospace industry by:
   (a) Masts which extend across stream lines and which discharge vapors into the free stream;
   (b) Masts which discharge rearward into a generated wake such as by a wing; and
   (c) Flush vents which discharge into a surface boundary layer.

2. Combustible mixtures can exist in aircraft fuel tanks, vent lines, and vent exits. On the basis of laboratory data with quiescent fuel-air mixtures lightning induced corona discharge streamers are capable of igniting such mixtures. The energy available in a lightning strike is many orders of magnitude greater than that required for ignition.

3. Available information is not adequate for a vent design specifically aimed to achieve maximum safety against vent fire and explosion hazards. This view was also held by all aerospace industry firms canvassed in the course of the investigation.

4. Available theoretical or experimental data on mixing of the vented vapors with the slipstream do not allow dependable determination of a fuel-air mixture profile in the vicinity of the vent exit.

5. Information on the effect of large energies on the probability of ignition and flame propagation is not available, particularly for mixtures considered to be outside the ignitable range.

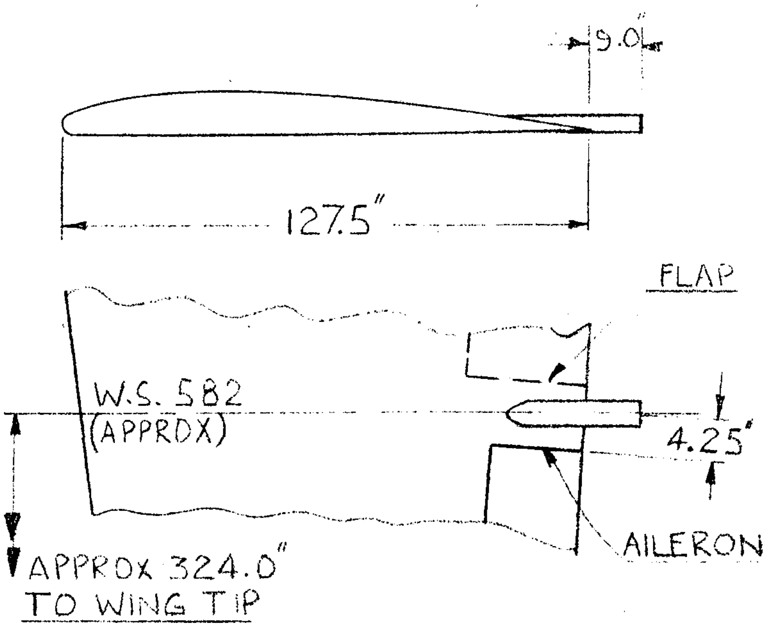
6. Information on pressure pulses generated in the near field by a lightning strike, on ignition of a vented mixture by such pressure pulses and on vent inflow phenomena caused by near lightning strikes is not available.

7. Flame quenching in the vent system for a high velocity gas stream is unsupported by either theoretical or experimental data.

8. Information on atmospheric electricity including corona, lightning streamers, and direct lightning strikes on aircraft are limited and should be extended.

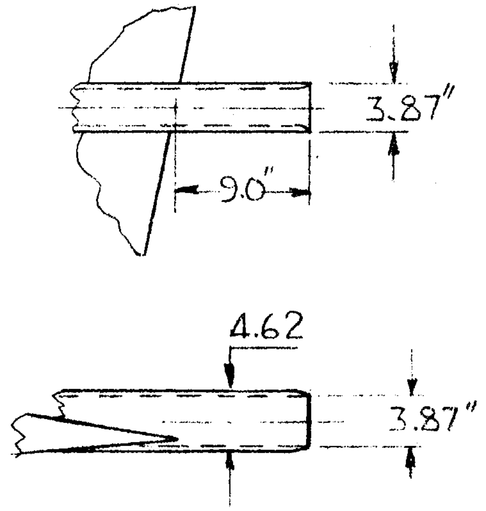
9. Investigation of ignition and vapor mixing phenomena associated with possible fire and explosion hazards under study in the present project should be made with the three configurations noted in paragraph 1 above.

Figure 1

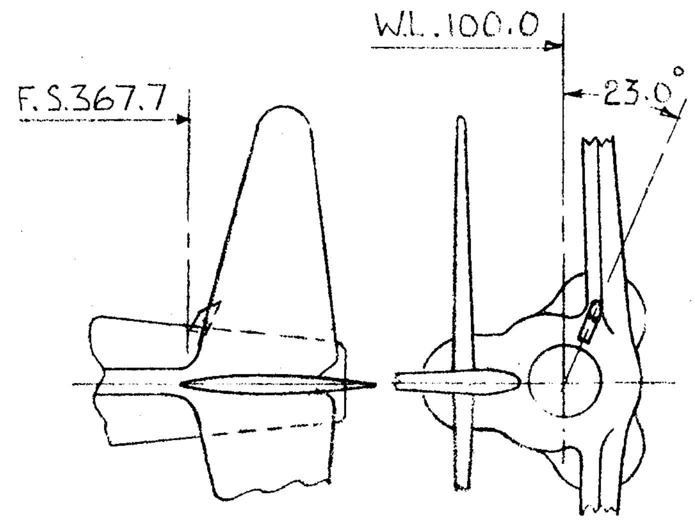


MODEL A

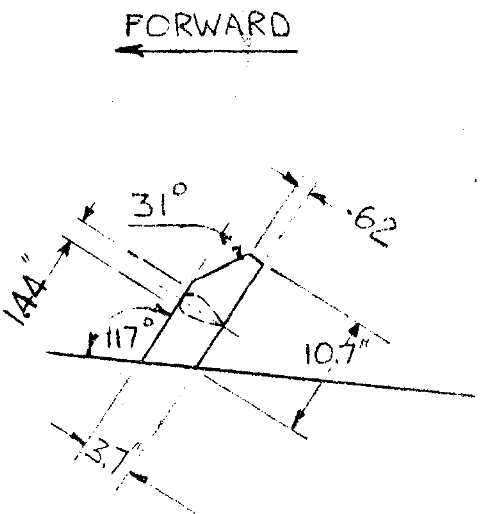
FIG. 1 (a)



DETAILS OF EXIT



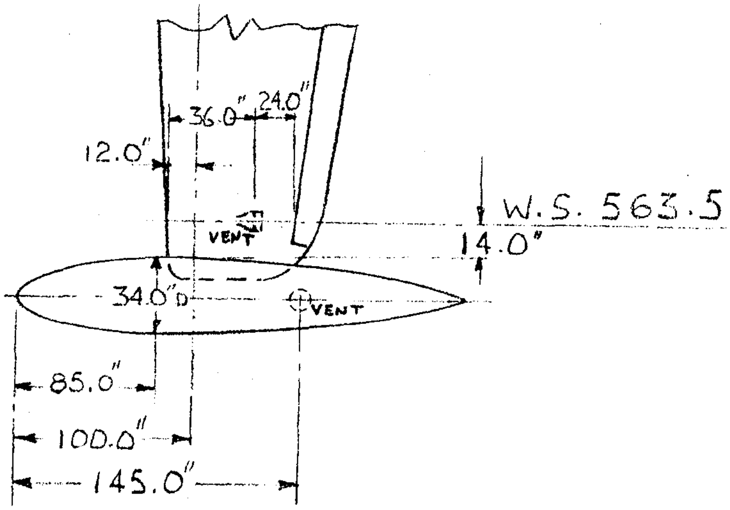
MODEL B



DETAILS OF EXIT MAST

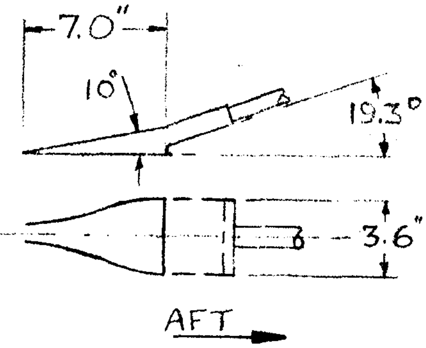
FIG. 1 (b)

Figure 1

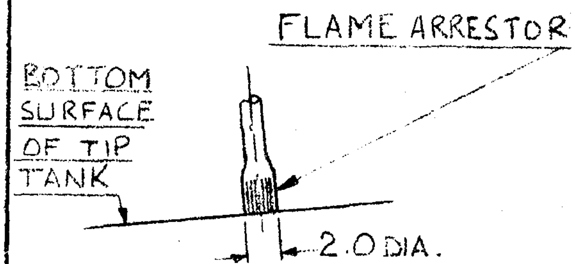


MODEL C

FIG. 1 (c)



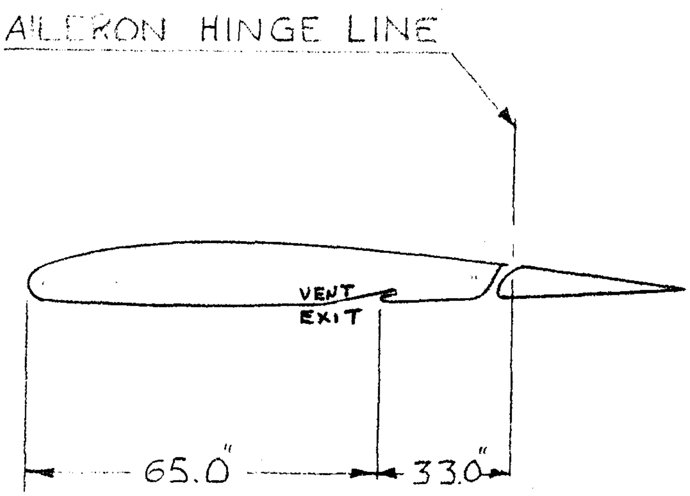
WING EXIT



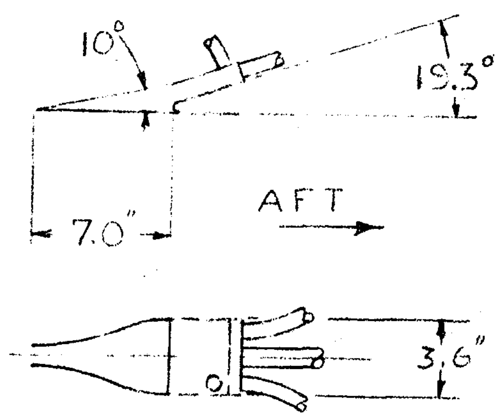
TIP TANK EXIT

DETAILS OF EXITS

MODEL D



SECTION APPROXIMATELY 12.0" FROM WING TIP

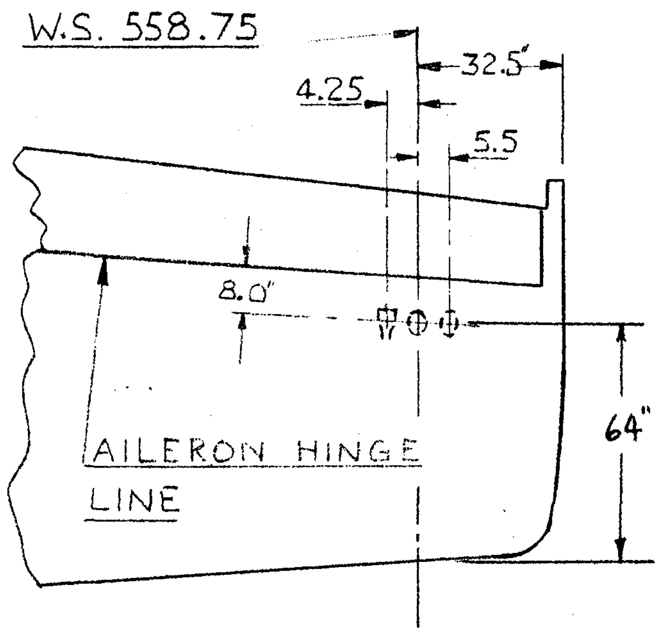


DETAILS OF EXIT

FORM 5767A-1

FIG. 1 (d)

Figure 1



MODEL E

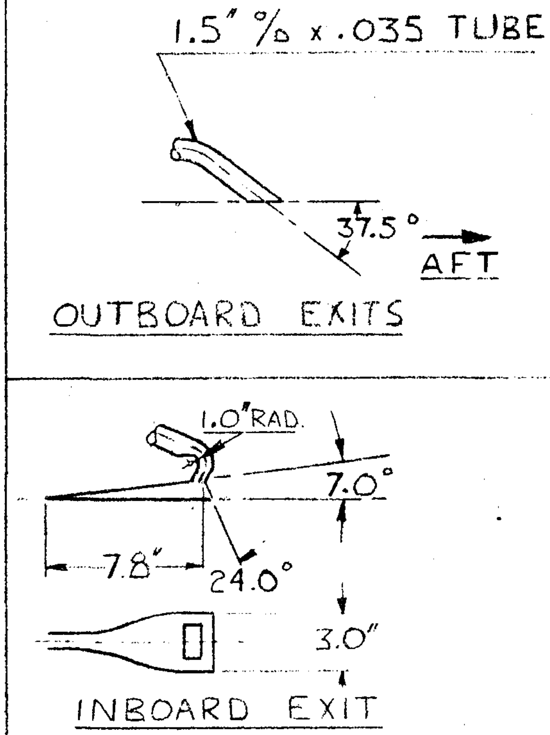
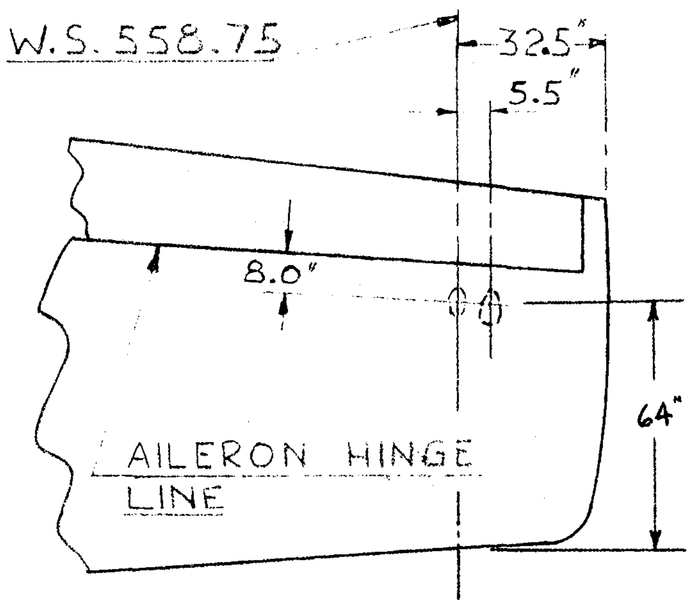


FIG. 1 (e)

DETAILS OF EXITS



MODEL F

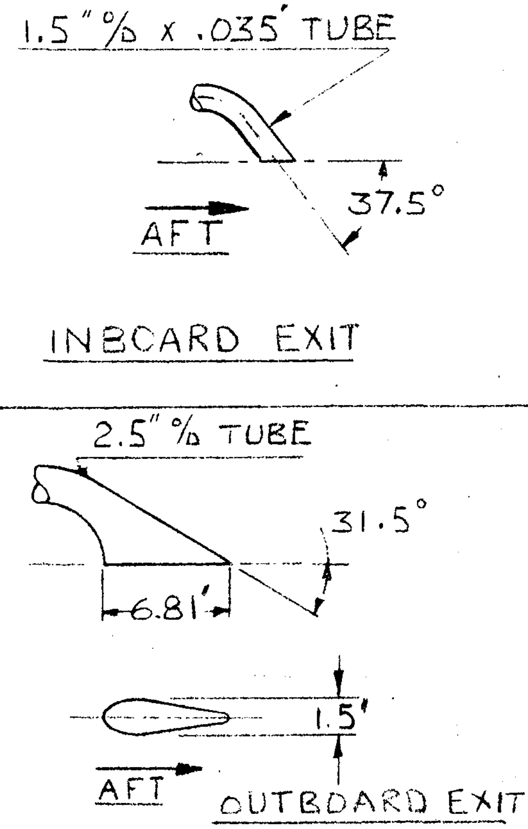


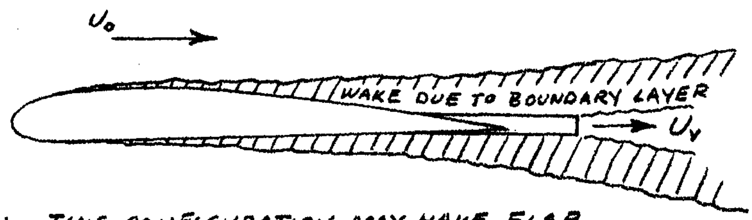
FIG. 1 (f)

DETAILS OF EXITS

FIG. 2

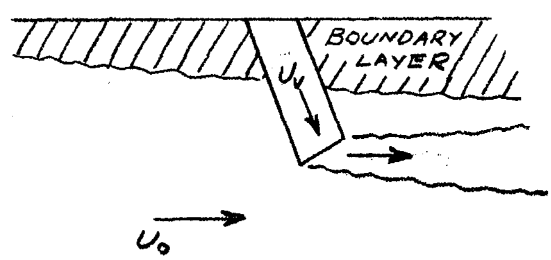
THREE GENERAL CLASSES OF FUEL VENT EXITS.

A. MAST DISCHARGING INTO A WAKE.

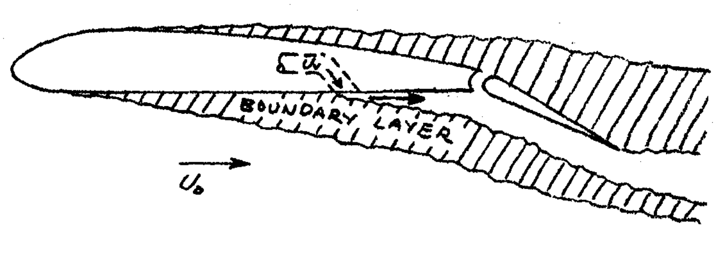


NOTE: THIS CONFIGURATION MAY HAVE FLAP, AILERON, OR BOTH, ADJACENT TO THE VENT MAST TO DISTURB FLOW PATTERN.

B. MAST DISCHARGING INTO FREE STREAM.



C. FLUSH VENT DISCHARGING INTO SURFACE BOUNDARY LAYER.



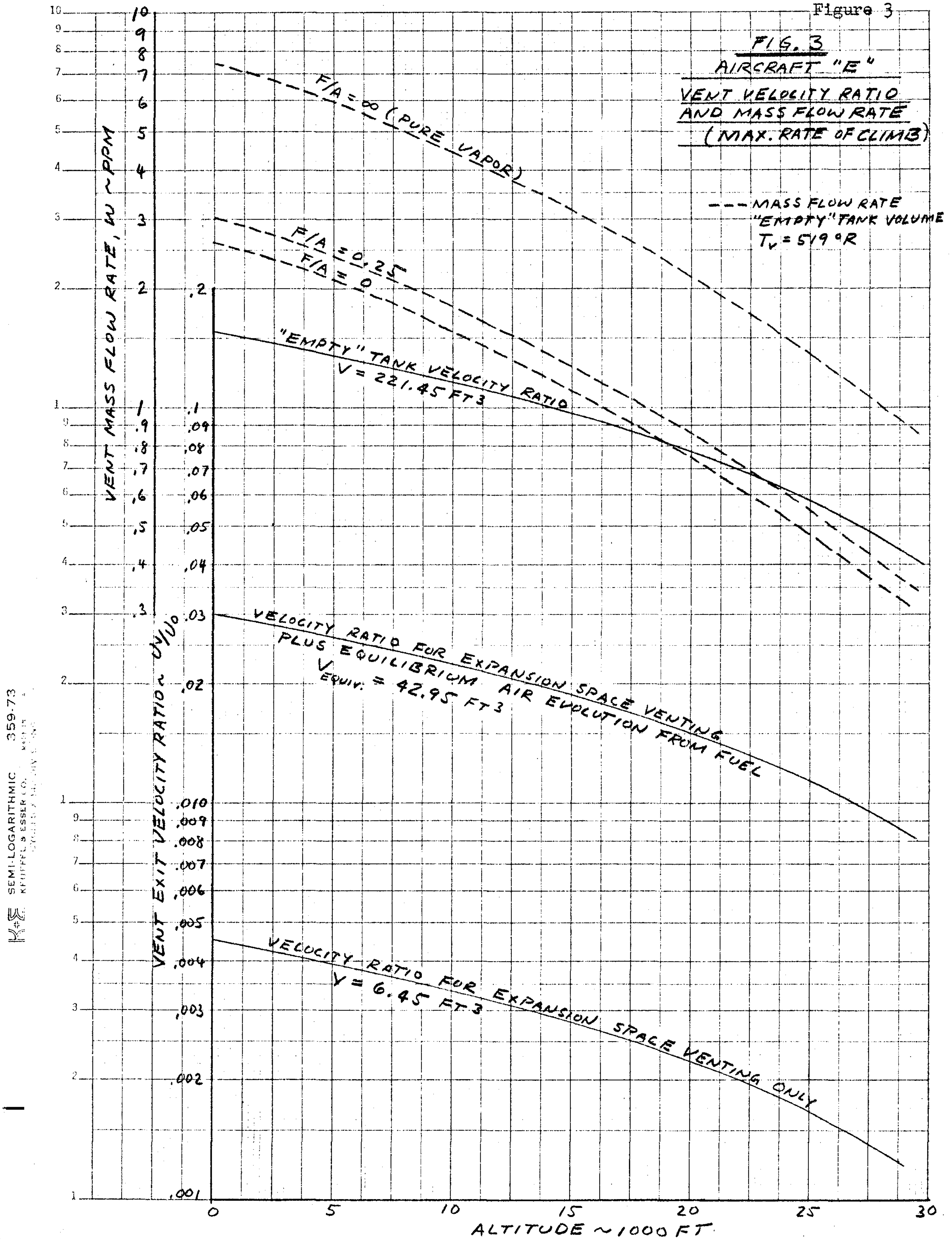


FIG. 3
AIRCRAFT "E"
VENT VELOCITY RATIO AND MASS FLOW RATE (MAX. RATE OF CLIMB)
--- MASS FLOW RATE "EMPTY" TANK VOLUME
T_v = 519 °R
F/A = ∞ (PURE VAPOR)
F/A = 0.25
F/A = 0
"EMPTY" TANK VELOCITY RATIO
V = 221.45 FT3
VELOCITY RATIO FOR EXPANSION SPACE VENTING PLUS EQUILIBRIUM AIR EVOLUTION FROM FUEL
$V_{EQUIV.}$ = 42.95 FT3
VELOCITY RATIO FOR EXPANSION SPACE VENTING ONLY
V = 6.45 FT3
VENT MASS FLOW RATE, W ~ PPM
VENT EXIT VELOCITY RATIO ~ U_V/U_0
ALTITUDE ~ 1000 FT
0
5
10
15
20
25
30
10
9
8
7
6
5
4
3
2
1
.9
.8
.7
.6
.5
.4
.3
.2
.1
.09
.08
.07
.06
.05
.04
.03
.02
.010
.009
.008
.007
.006
.005
.004
.003
.002
.001
SEMI-LOGARITHMIC 359-73
KEUFFEL & ESSER CO.

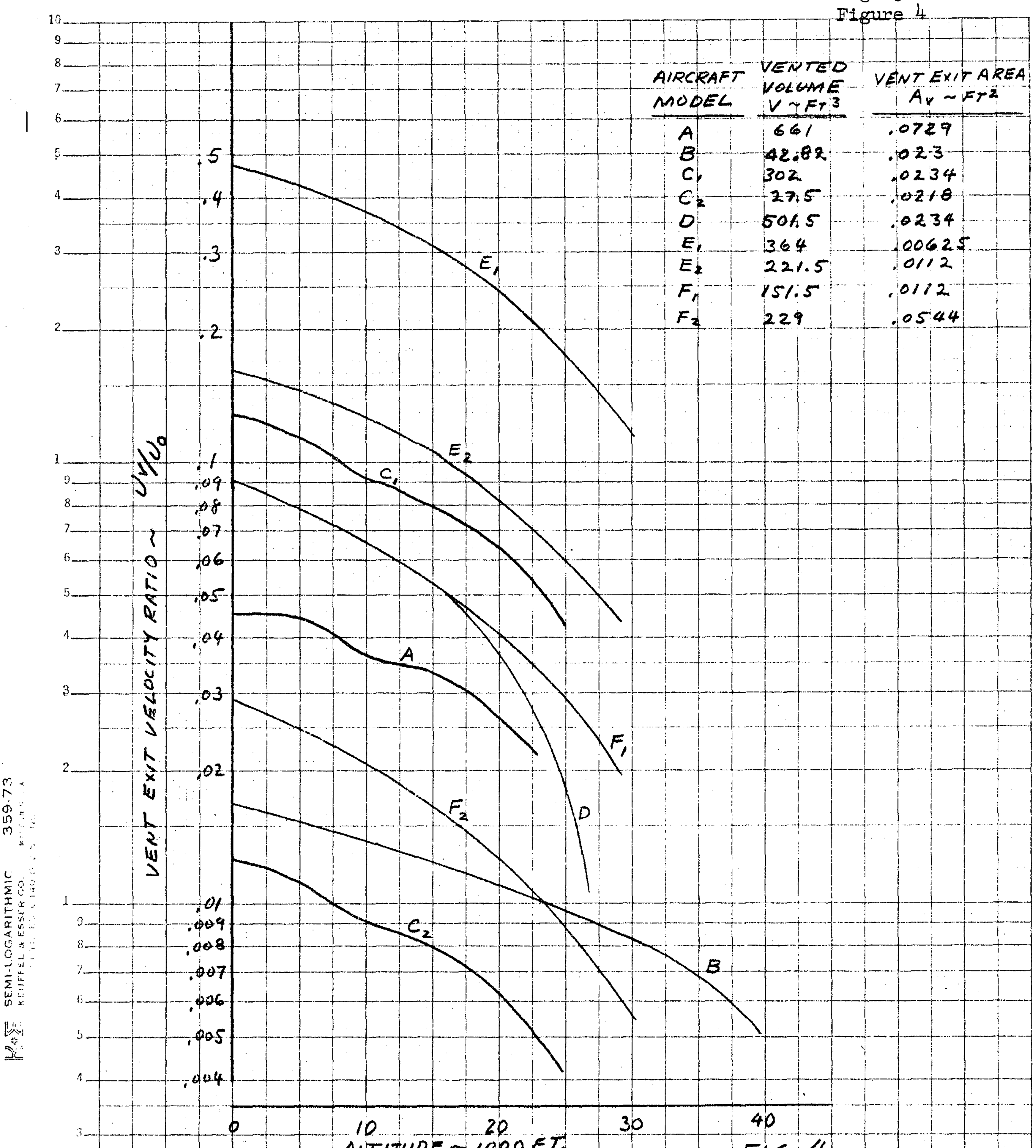


FIG. 4

SUMMARY OF VENT EXIT VELOCITY RATIO FOR 6 AIRPLANES AT MAX. RATE OF CLIMB (NON-FUEL BOILING)

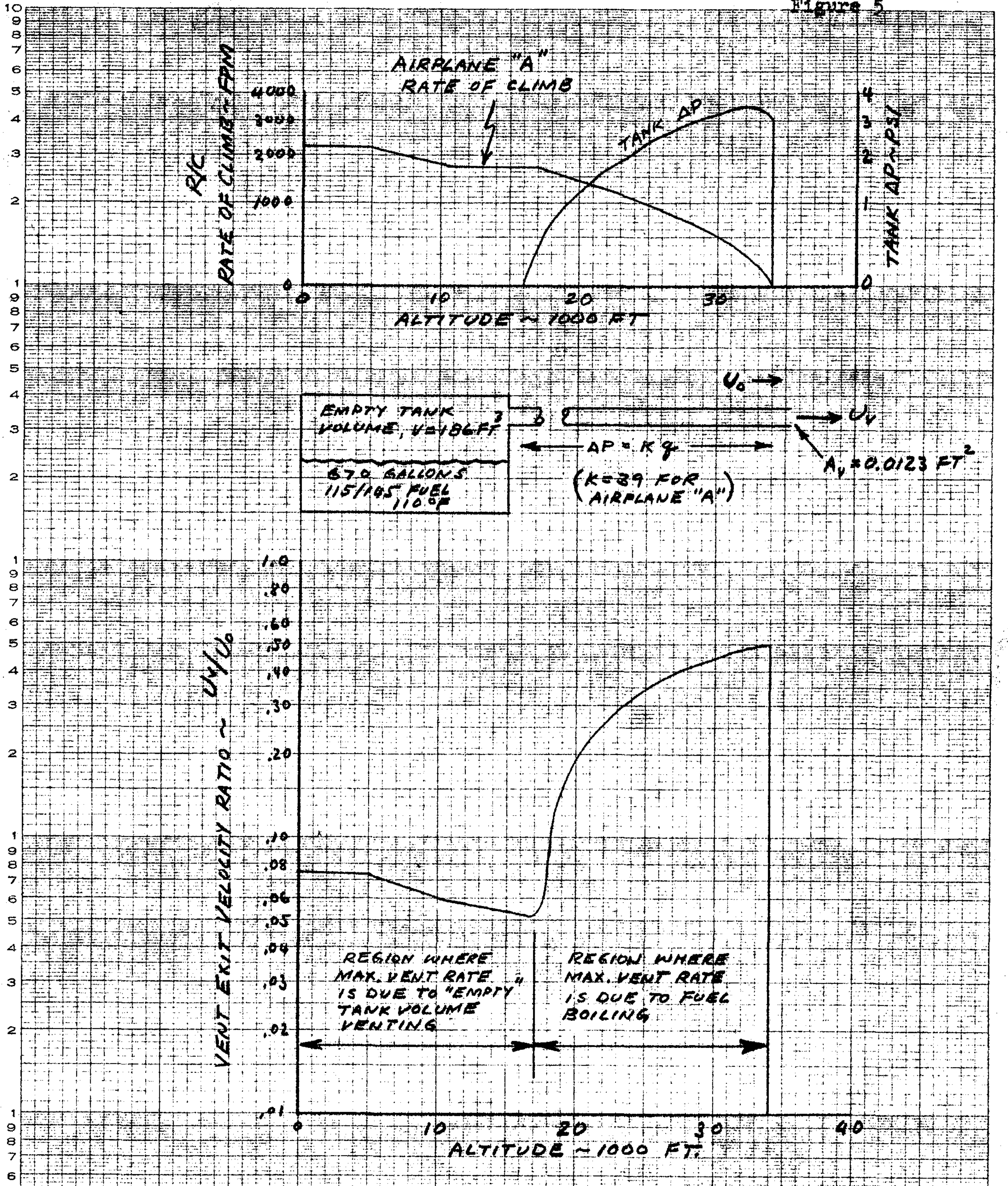
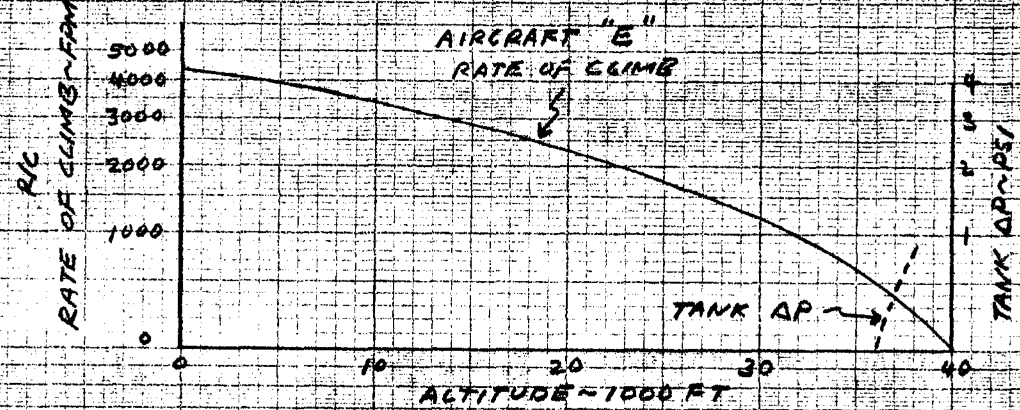


FIG. 5

VENT EXIT VELOCITY RATIO FOR A SPECIAL CASE OF AIRCRAFT "A"



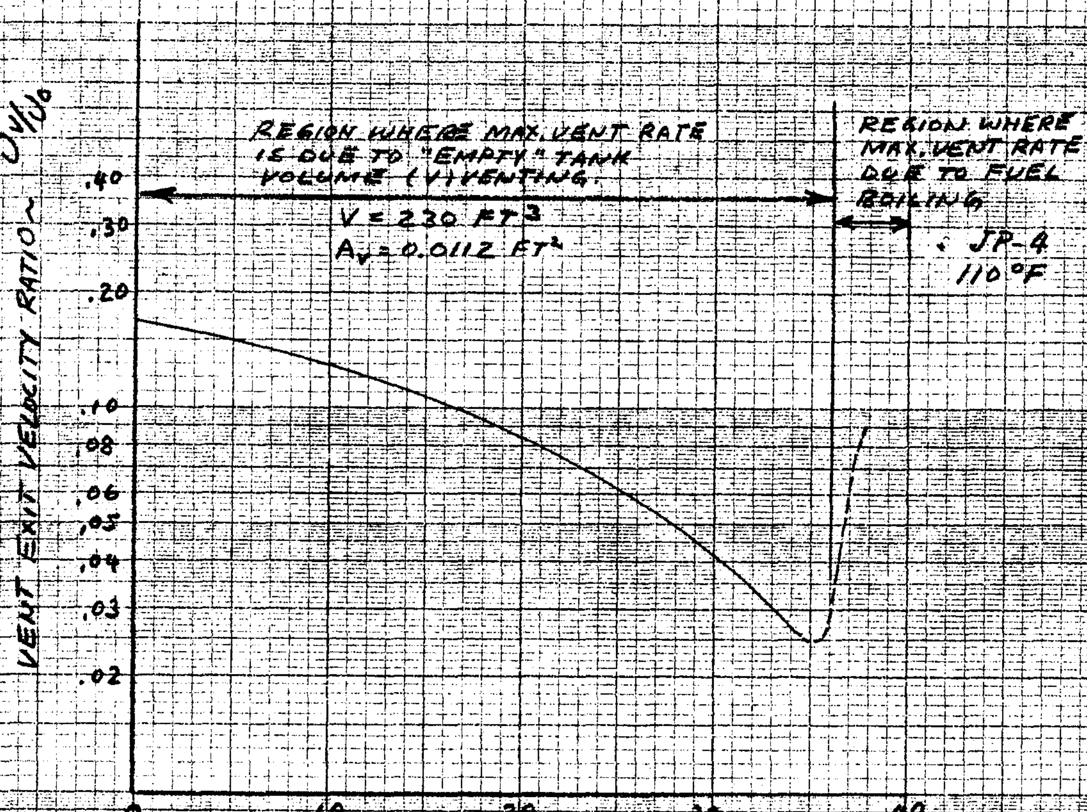


FIG. 6
VENT EXIT VELOCITY RATIO
AIRCRAFT "E"

Figure 7

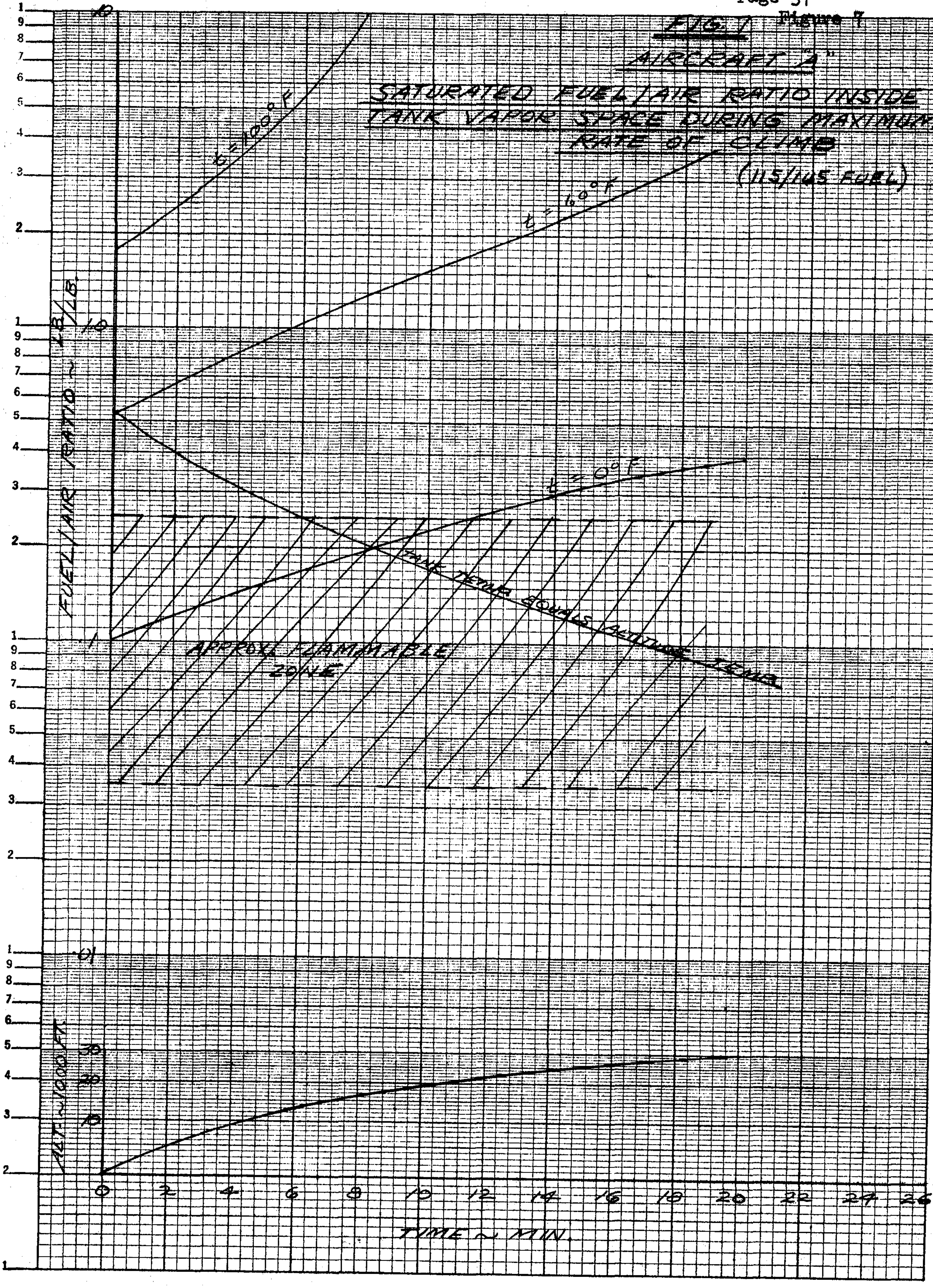


FIG. 7
AIRCRAFT "A"
SATURATED FUEL/AIR RATIO INSIDE TANK VAPOR SPACE DURING MAXIMUM RATE OF CLIMB
(115/145 FUEL)
t = 100°F
t = 60°F
t = 0°F
TANK TEMP. EQUALS ALTITUDE TEMP.
APPROX. FLAMMABLE ZONE
FUEL/AIR RATIO ~ LB/LB
ALT ~ 1000 FT.
TIME ~ MIN.
10
1.0
.1
.01
30
20
10
0
2
4
6
8
10
12
14
16
18
20
22
24
26

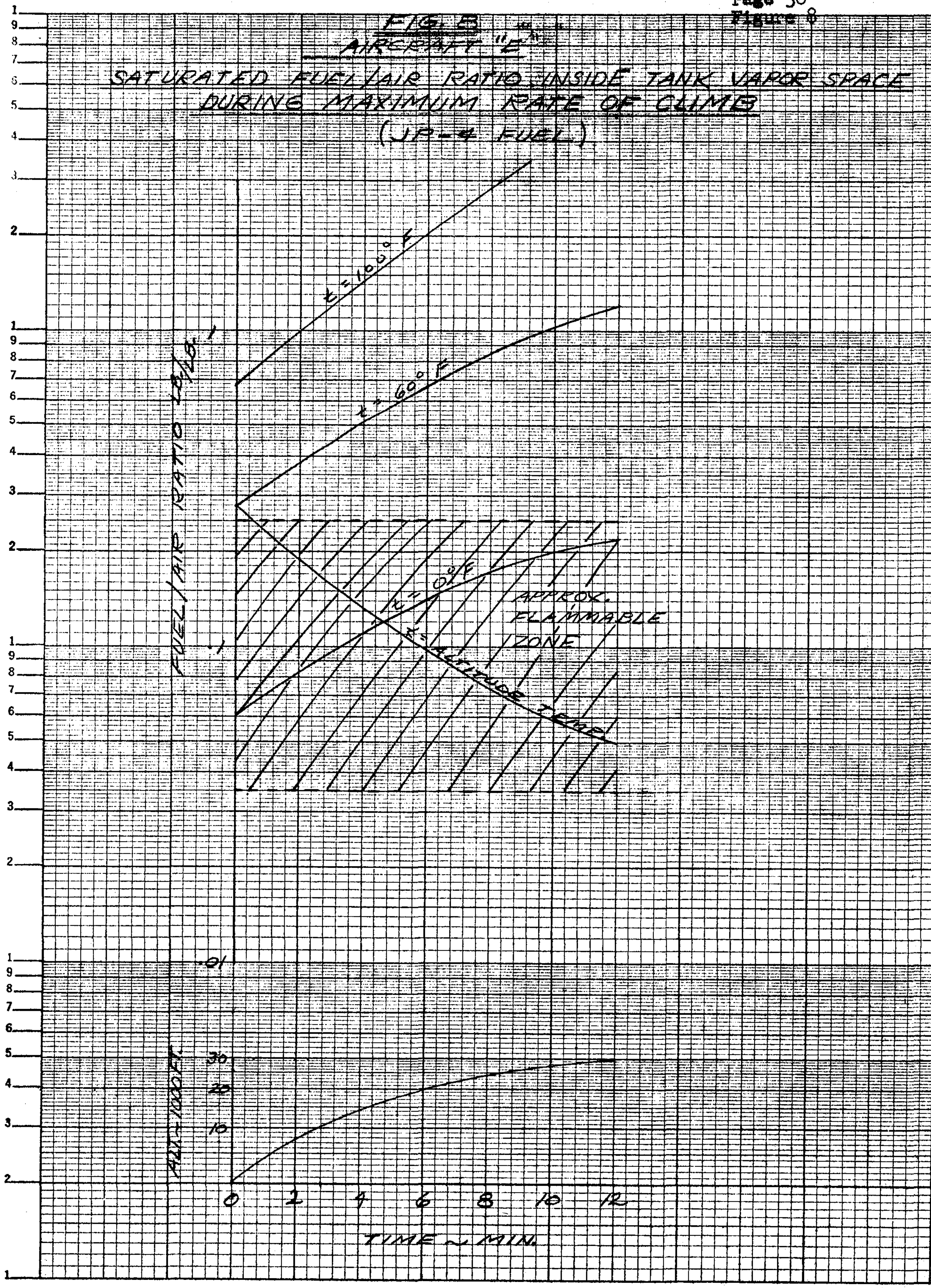


FIG. 8
AIRCRAFT "E"
SATURATED FUEL/AIR RATIO INSIDE TANK VAPOR SPACE
DURING MAXIMUM RATE OF CLIMB
(JP-4 FUEL)
t = 100° F
t = 60° F
t = 0° F
t = ALTITUDE TEMP.
APPROX. FLAMMABLE ZONE
FUEL/AIR RATIO LB./LB.
1
.1
.01
ALT.~1000 FT.
30
20
10
0
2
4
6
8
10
12
TIME ~ MIN.
SEMI-LOGARITHMIC 359-81
KEUFFEL & ESSER CO. MADE IN U.S.A.
4 CYCLES X 70 DIVISIONS

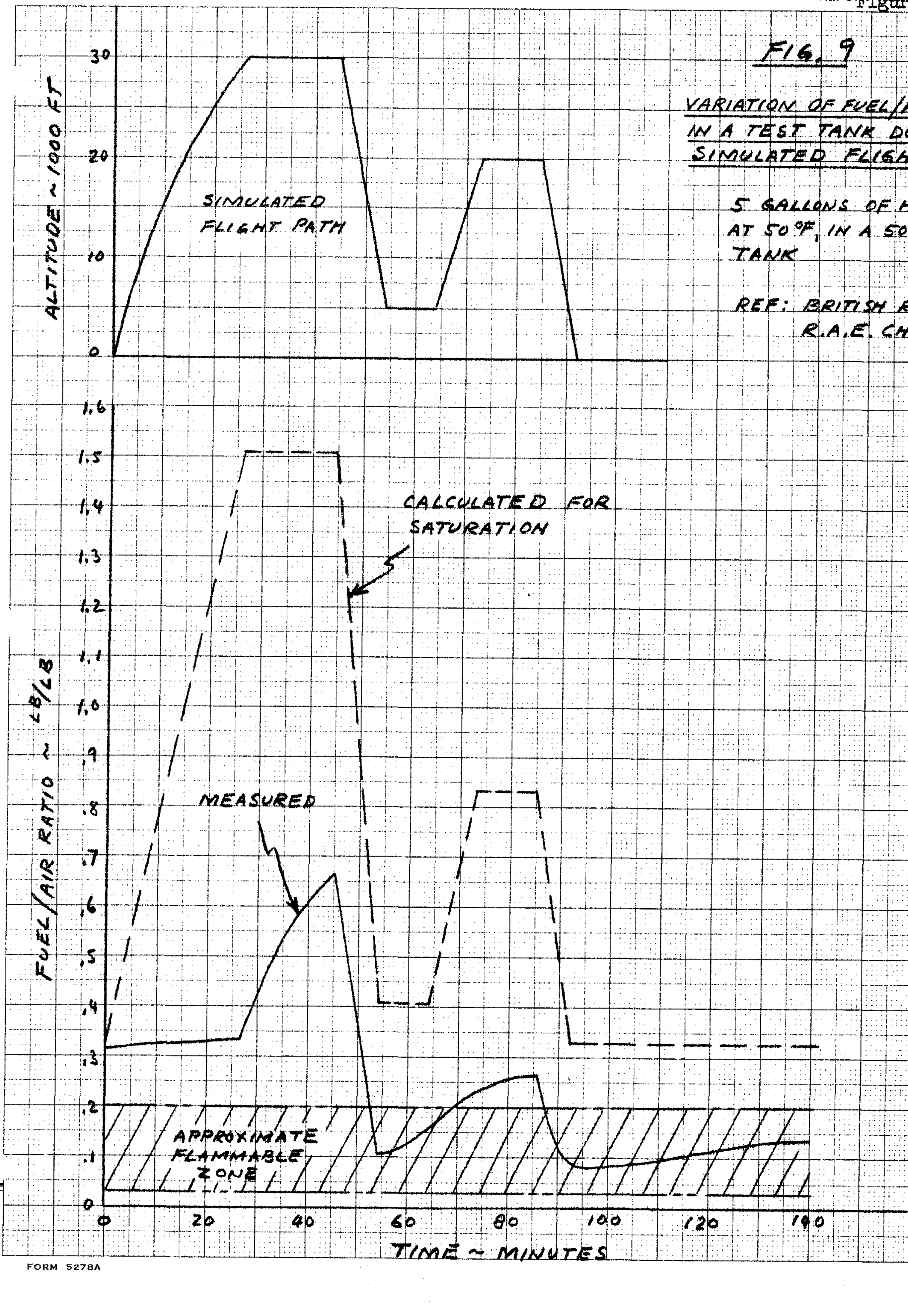


FIG. 9
VARIATION OF FUEL/AIR RATIO IN A TEST TANK DURING SIMULATED FLIGHT
5 GALLONS OF HEXANE AT 50°F, IN A 50 GALLON TANK
REF: BRITISH REPORT R.A.E. CH 650
ALTITUDE ~ 1000 FT
30
20
10
0
SIMULATED FLIGHT PATH
FUEL/AIR RATIO ~ LB/LB
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
CALCULATED FOR SATURATION
MEASURED
APPROXIMATE FLAMMABLE ZONE
0
20
40
60
80
100
120
140
TIME ~ MINUTES

Lockheed AIRCRAFT CORPORATION

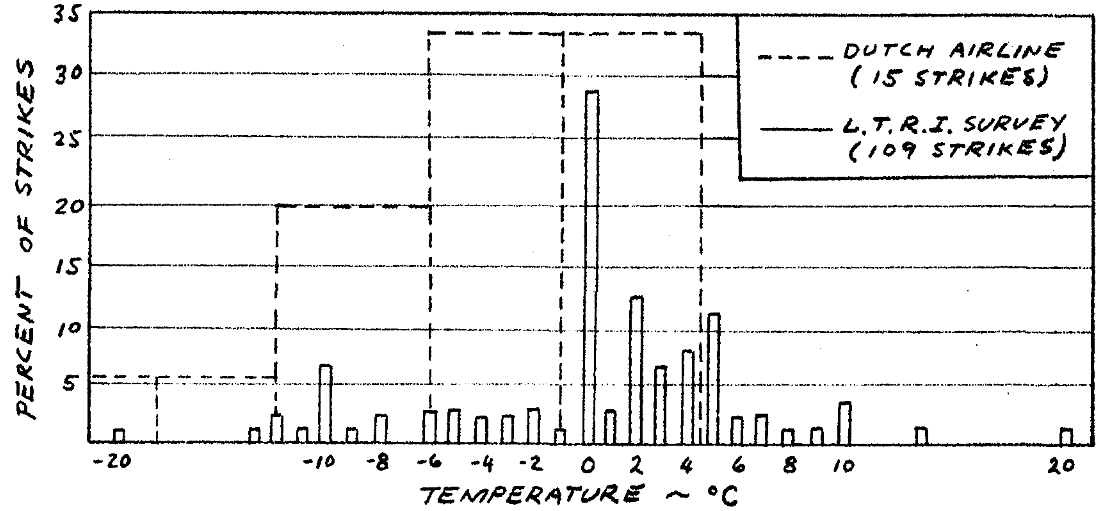
CALIFORNIA DIVISION

FIG. 10

VARIATION OF PERCENTAGE OF LIGHTNING STRIKES TO AIRCRAFT WITH TEMPERATURE AND ALTITUDE.

REFERENCE: 1. LIGHTNING HAZARDS TO AIRCRAFT FUEL TANKS
LIGHTNING & TRANSIENTS RESEARCH INST.
NACA TN 4326

2. LIGHTNING & STATIC DISCHARGE REPORT
WITH REGARD TO K.L.M. AIRPLANES
1-22-53 TW-1186 REPORT NO. 2



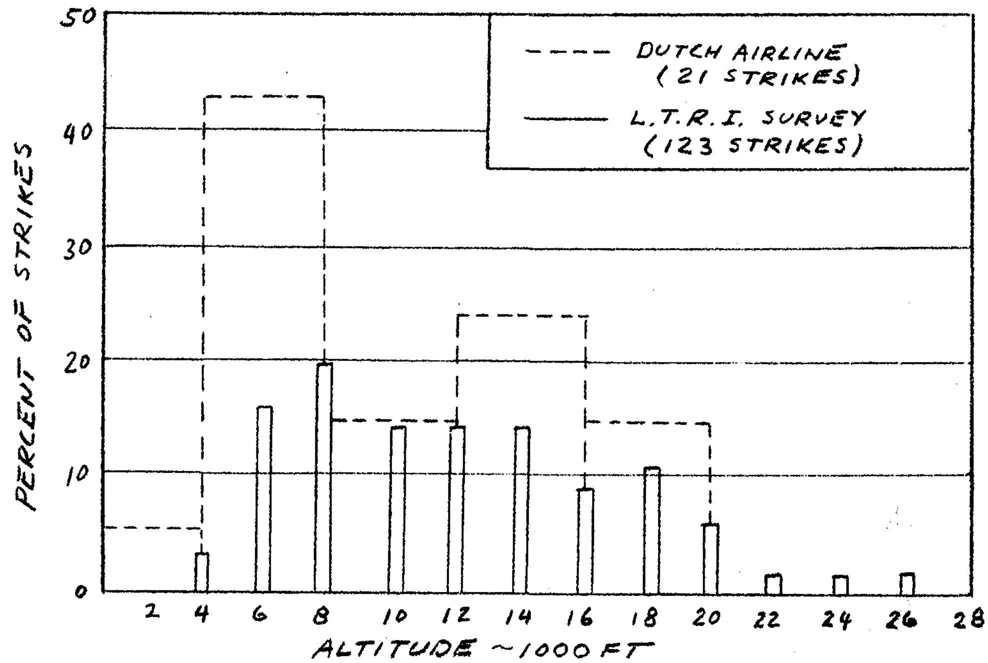


FIG. 11

MAP OF FUEL/AIR RATIO DUE TO MIXING OF GAS JET WITH AIR STREAM (VELOCITY RATIO, $\frac{U_V}{U_0} = 4.0$)

REFERENCE: MOMENTUM AND MASS TRANSFER IN COAXIAL GAS JETS
WALTON FORSTALL JR. AND A.H. SHAPIRO
JOURNAL OF APPLIED MECHANICS - DEC, 1950

$$\frac{\psi}{\psi_V} = \frac{1}{2}\left(\frac{L}{X/D}\right)\left(1+\cos\theta\right) \quad \text{FOR } X/D > L$$

$L = 4 + 12\lambda$ = POTENTIAL CORE (IN JET DIAMETERS)

$\theta = \frac{\pi}{2}\left(\frac{y}{R}\right)\left(\frac{L}{X/D}\right)^{1-\lambda}$

ψ = MIXED FUEL/AIR RATIO (FRACTION OF STOICHIOMETRIC)

ψ_V = JET EXIT FUEL/AIR RATIO (")

U_0 = STREAM VELOCITY

U_V = JET EXIT VELOCITY

$\lambda = U_0/U_V = 1/4$

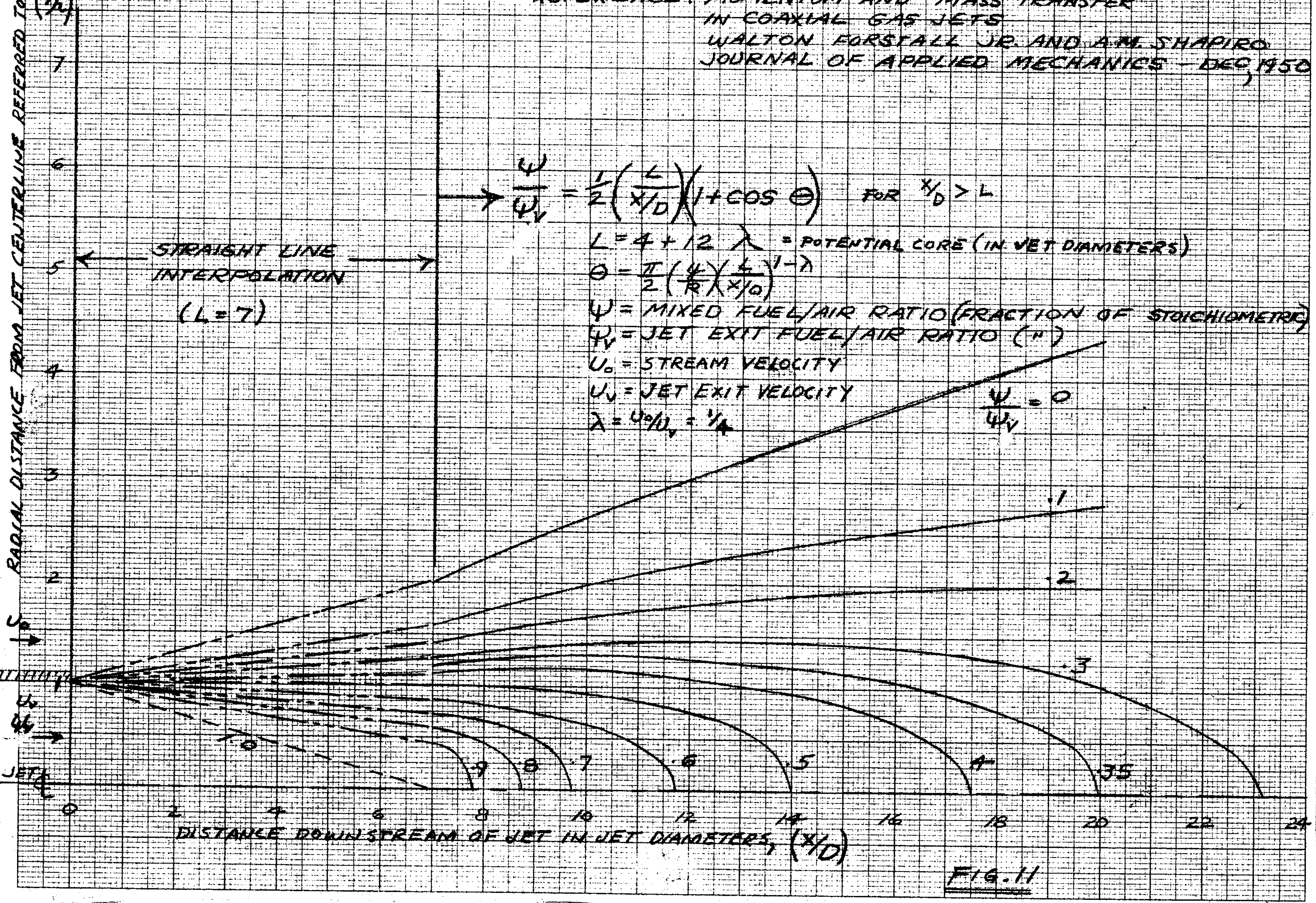


FIG. 11

FIG. 12

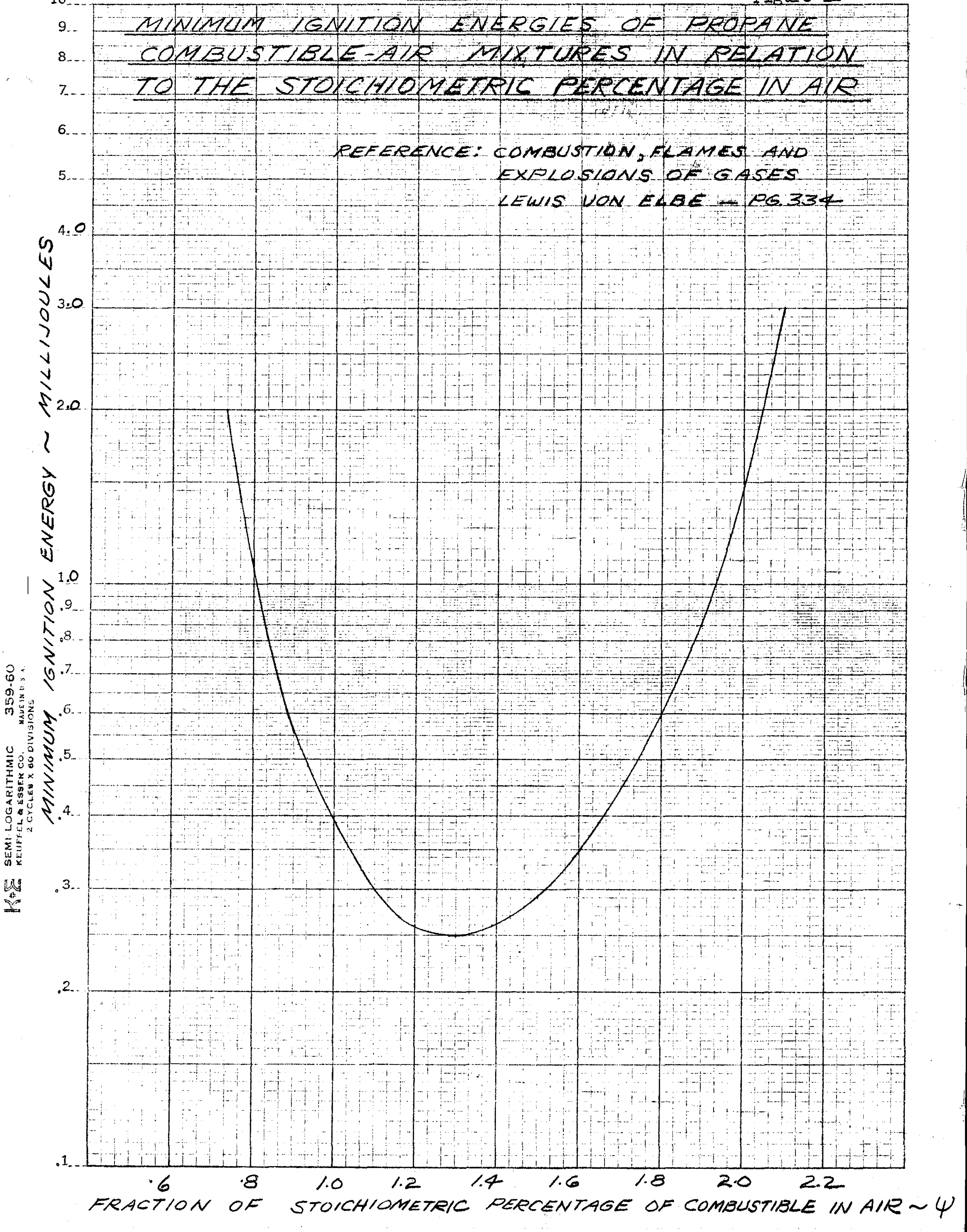

MINIMUM IGNITION ENERGIES OF PROPANE
COMBUSTIBLE-AIR MIXTURES IN RELATION
TO THE STOICHIOMETRIC PERCENTAGE IN AIR
REFERENCE: COMBUSTION, FLAMES AND
EXPLOSIONS OF GASES
LEWIS VON ELBE — PG. 334
MINIMUM IGNITION ENERGY ~ MILLIJOULES
10
9
8
7
6
5
4.0
3.0
2.0
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
FRACTION OF STOICHIOMETRIC PERCENTAGE OF COMBUSTIBLE IN AIR ~ ψ
SEMI-LOGARITHMIC 359-60
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 CYCLES X 60 DIVISIONS

FIG. 13. IGNITION ENERGY MAP DOWNSTREAM OF A JET WHICH MIXES WITH A MOVING AIR STREAM

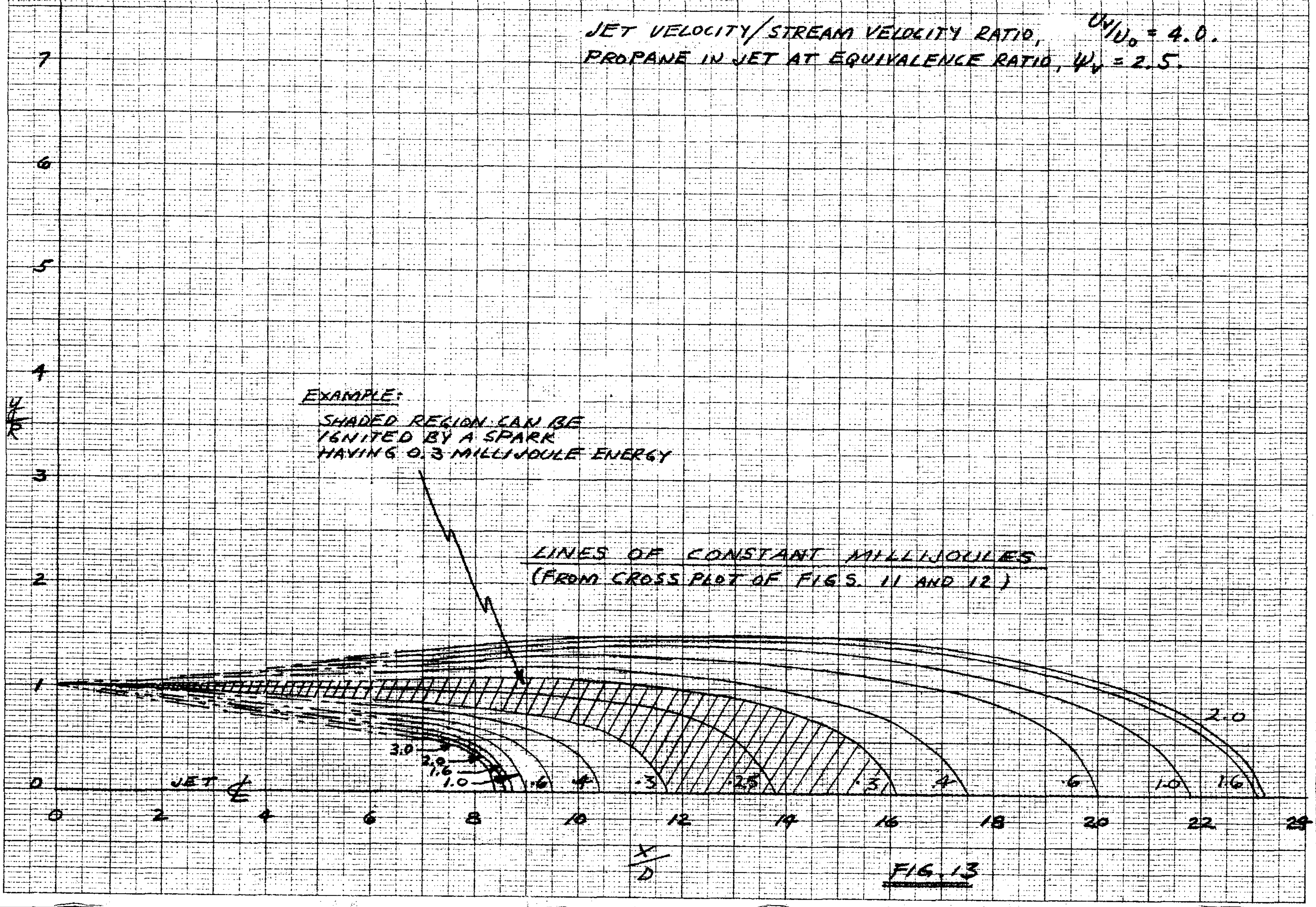


FIG. 13

FIG. 14

MINIMUM IGNITION ENERGY vs. ELECTRODE SPACING

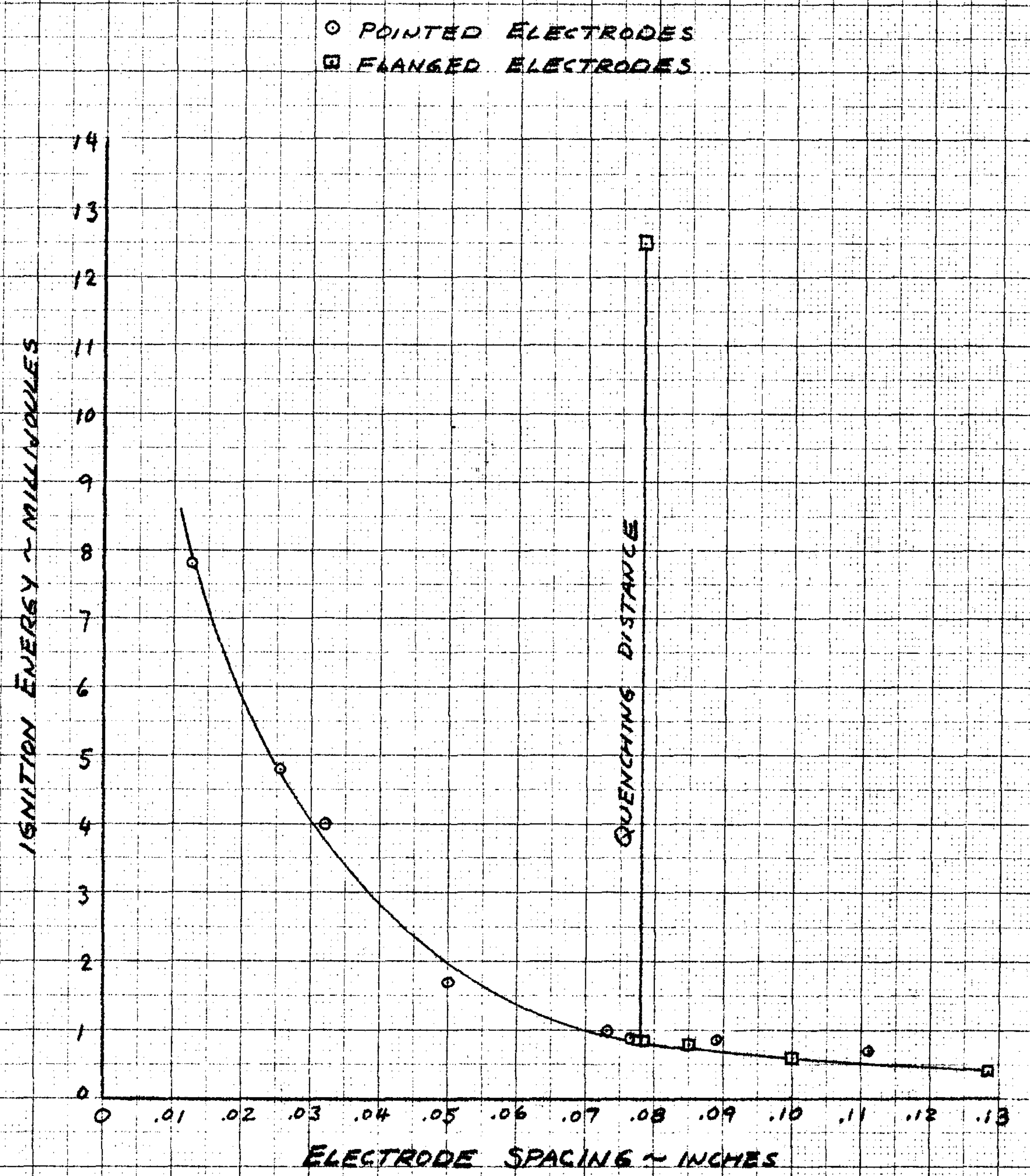
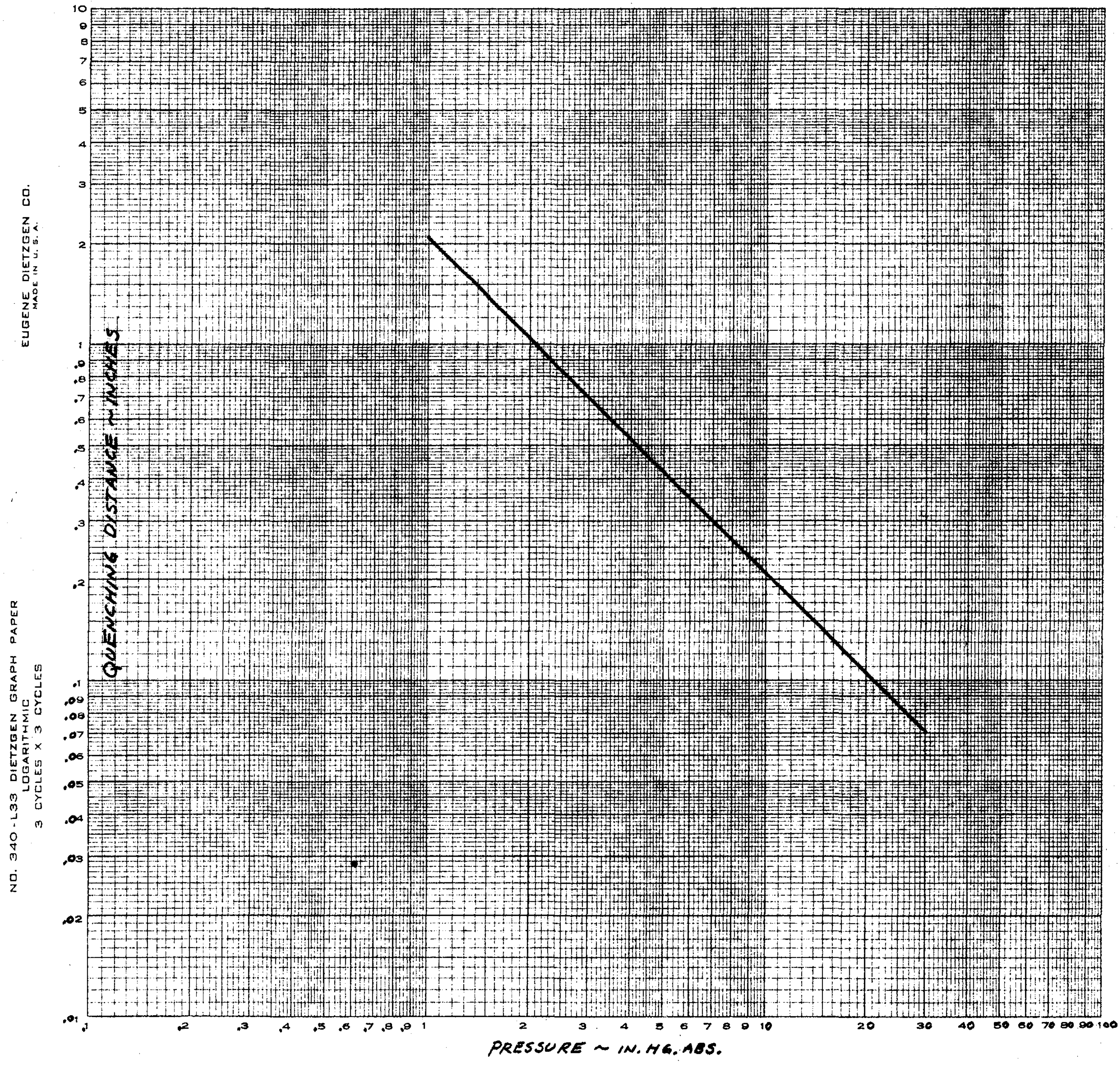


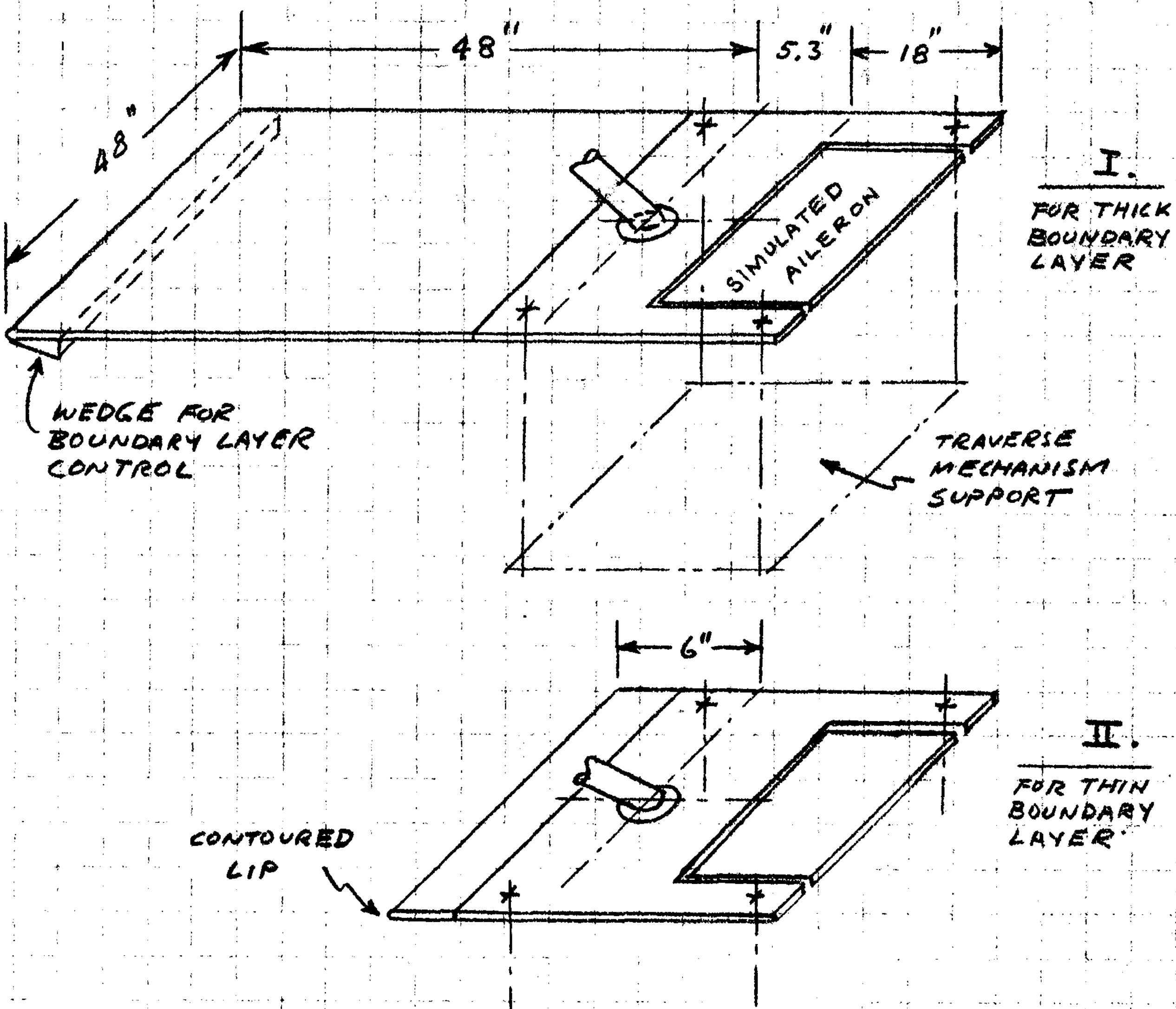
FIG. 15

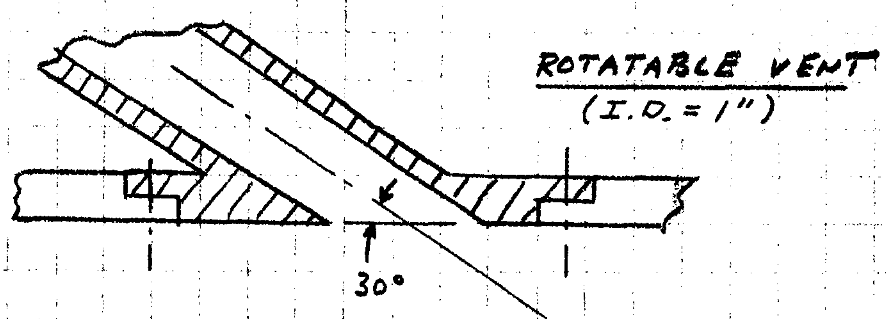
MINIMUM QUENCHING DISTANCE vs. PRESSURE
FOR PROPANE IN AIR 110% OF STOICHIOMETRIC



IAC/379280

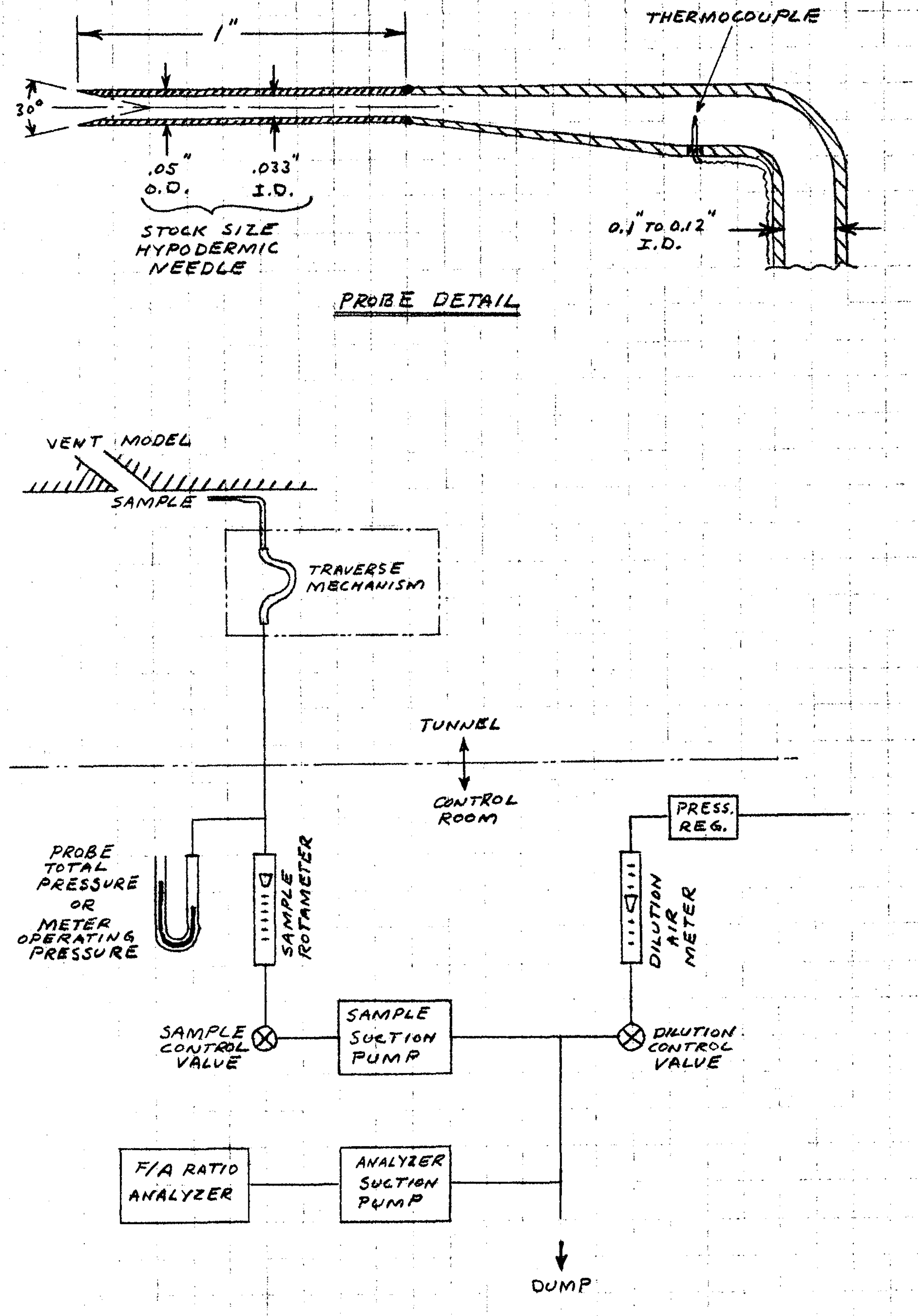
	NAME	DATE	LOCKHEED AIRCRAFT CORP. CALIFORNIA DIVISION	Page	TEMP.	PERM.
Prepared	BUSBY	10/26/61				
Checked			TITLE FIG. 16 TEST MODEL - CONFIG. "C"	Page 46		
Approved				Model		
				Report No. Figure 16		

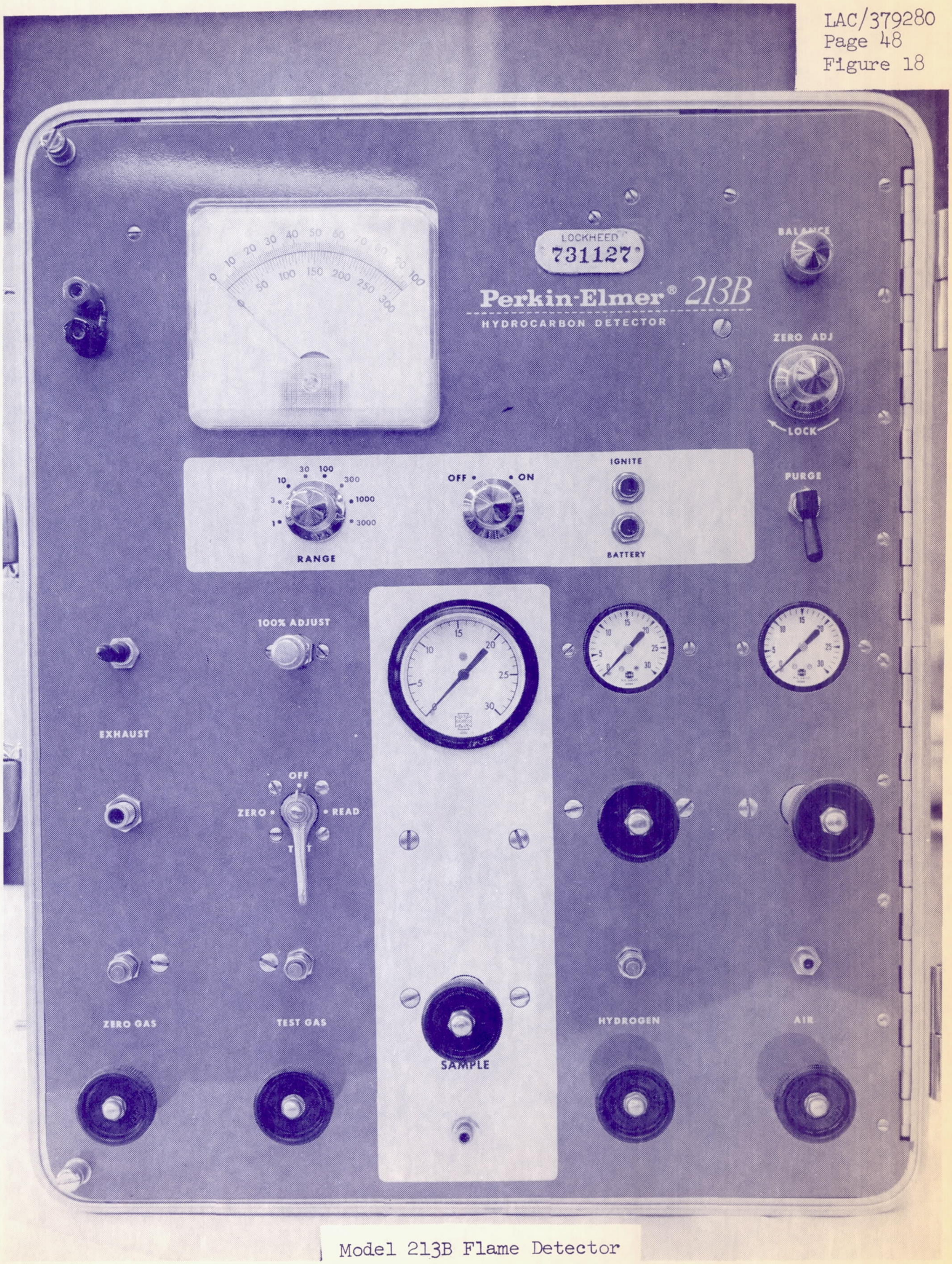




LAC/379280

Prepared	ALB	12/8/61	LOCKHEED AIRCRAFT CORP. CALIFORNIA DIVISION	Page 47
Checked			TITLE SAMPLE SYSTEM SCHEMATIC FIG. 19	Model Figure 17
Approved				Report No.





Model 213B Flame Detector

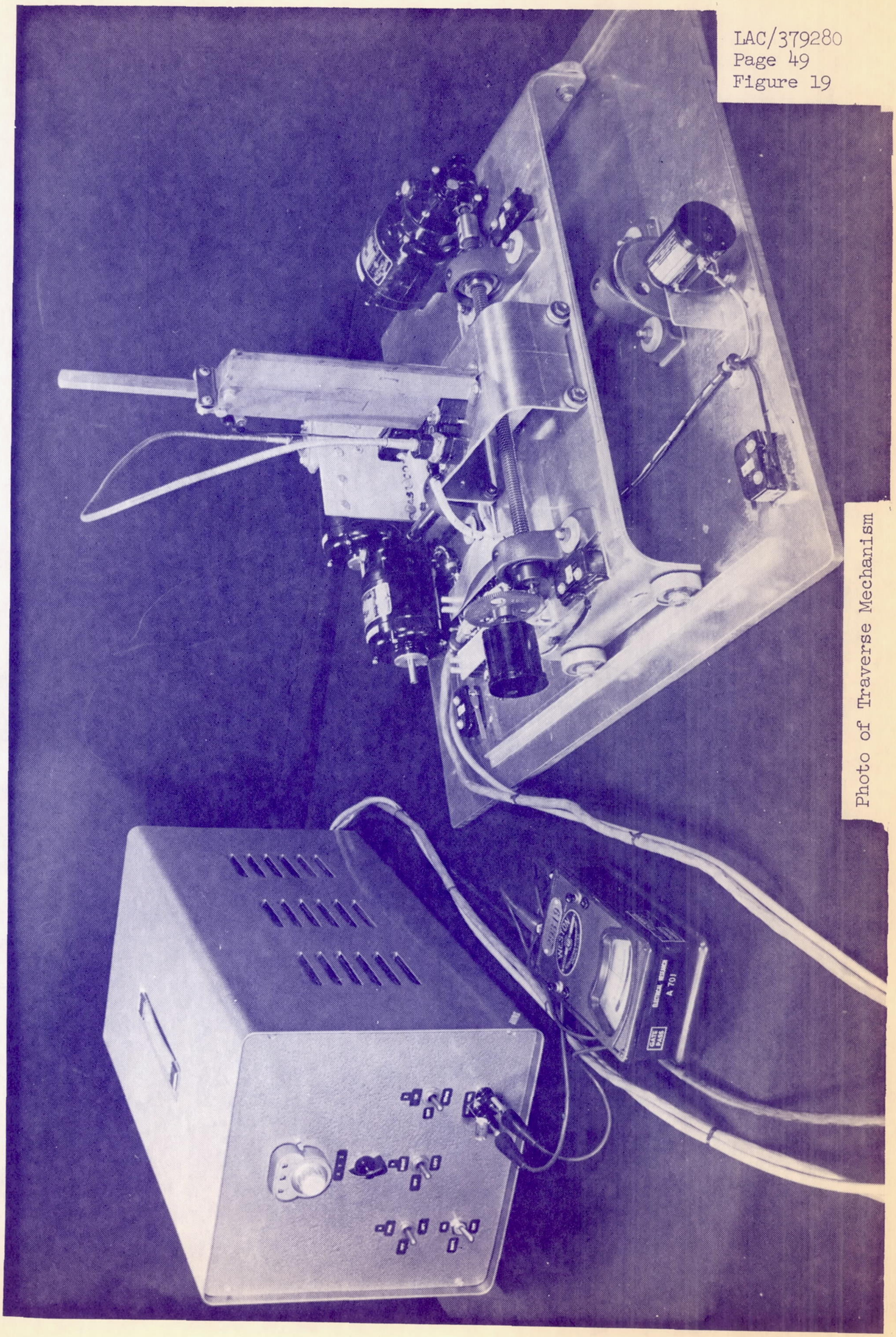


Photo of Traverse Mechanism

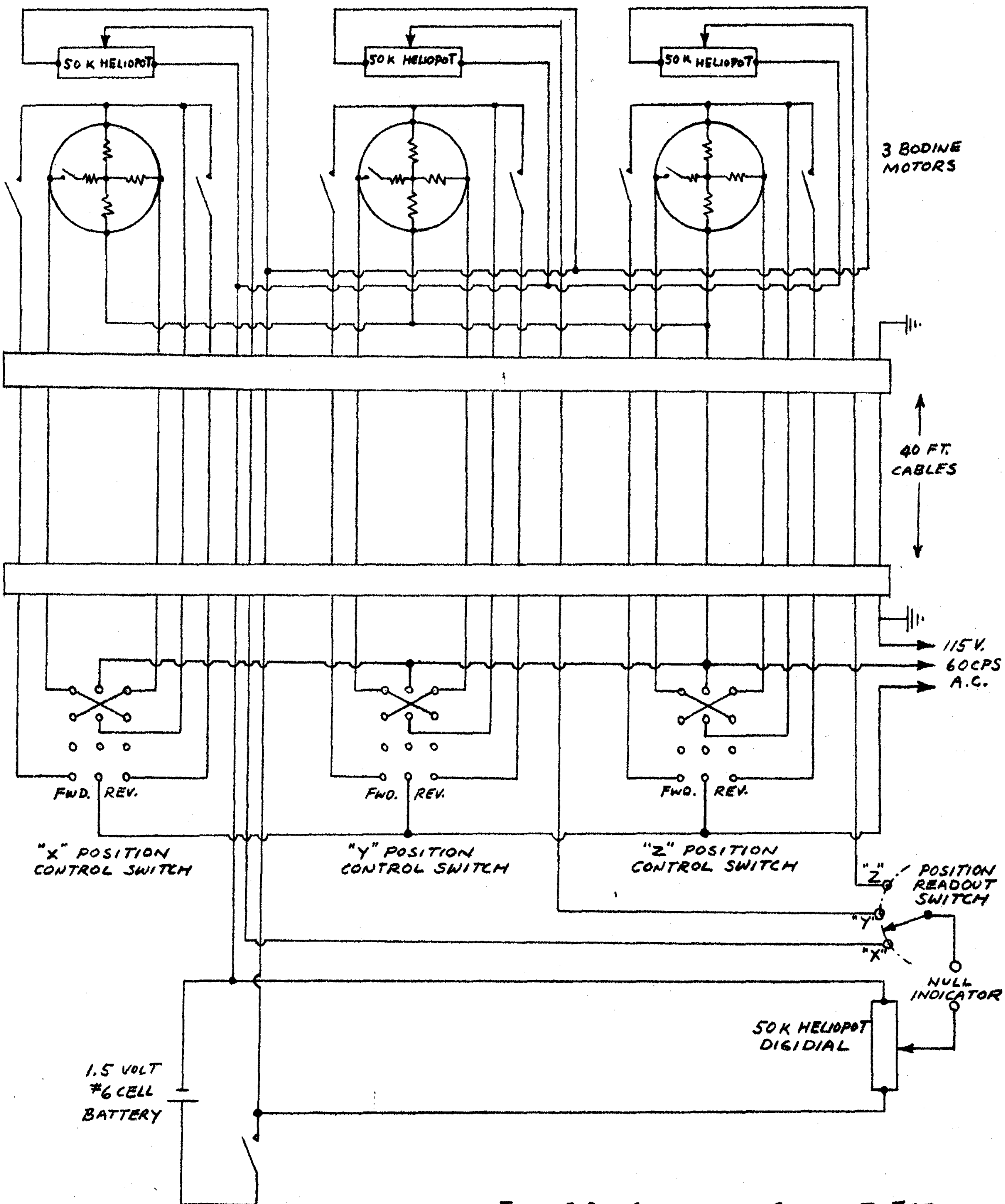


FIG. 20 CONTROL CIRCUIT FOR PROBE TRAVERSE MECHANISM